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Phase I Final Report: Titan Submarine

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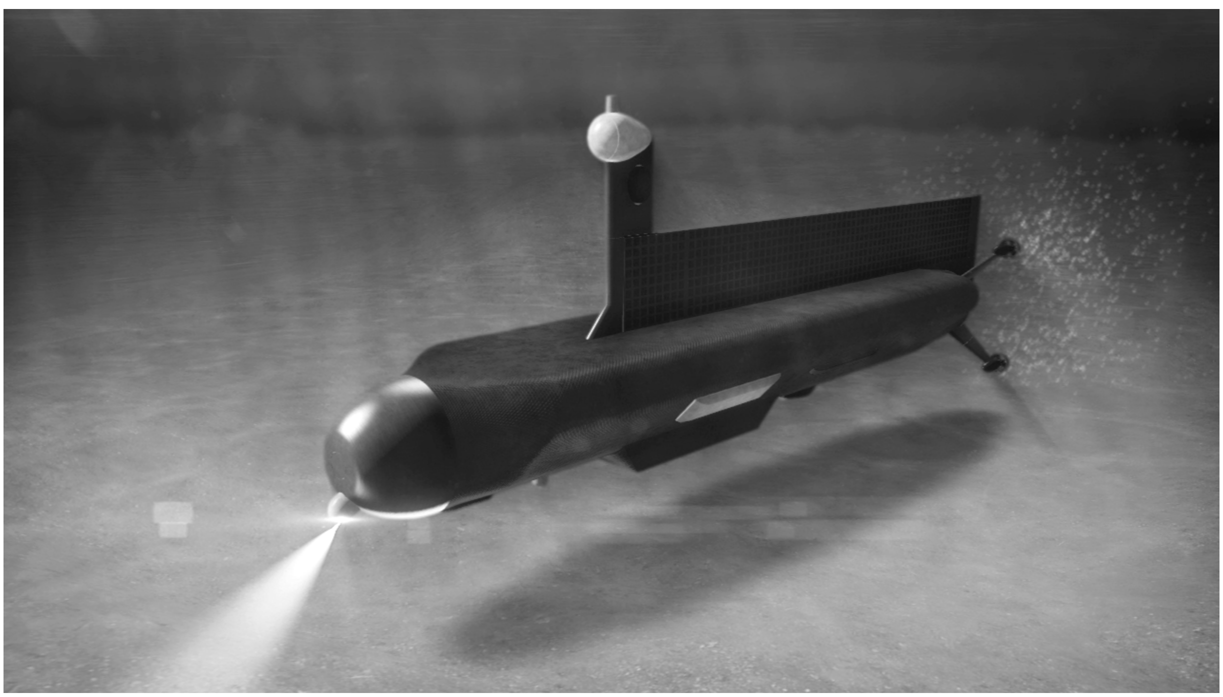

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Finally, a nod to dreamers such as Jules Verne who inspire us to explore new worlds: Mobilis in Glaciali!

This report contains preliminary findings,
subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

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Contents

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1.0 Executive Summary

The conceptual design of a submarine for Saturn's moon Titan was a funded NASA's Innovative Advanced Concepts (NIAC) Phase I for 2014. The effort investigated what science a submarine for Titan's liquid hydrocarbon ~93 K (–180 °C) seas might accomplish and what that submarine might look like. Focusing on a flagship class science system (~100 kg) it was found that a submersible platform can accomplish extensive and exciting science both above and below the surface of the Kraken Mare (Figure 1.1). The submerged science includes mapping using side looking sonar, imaging and spectroscopy of the sea at all depths, as well as sampling of the sea's bottom and shallow shoreline. While surfaced the submarine will not only sense weather conditions (including the interaction between the liquid and atmosphere) but also image the shoreline, as much as 2 km inland. This imaging requirement pushed the landing date to Titan's next summer period (~2047) to allow for continuous lighted conditions, as well as direct-to-Earth (DTE) communication, avoiding the need for a separate relay orbiter spacecraft. Submerged and surfaced investigation are key to understanding both the hydrological cycle of Titan as well as gather hints to how life may have begun on Earth using liquid/sediment/chemical interactions. An estimated 25 Mb of data per day would be generated by the various science packages. Most of the science packages (electronics at least) can be safely kept inside the submarine pressure vessel and warmed by the isotope power system.

The baseline 90 day mission would be to sail alternately submerged and surfaced around and through Kraken Mare investigating the shoreline and inlets to evaluate the sedimentary interaction both on the surface and below. Depths of Kraken have yet to be sensed (Ligeia to the north is thought to be 200 m (656 ft) deep), but a maximum depth of 1,000 m (3.281 ft) for Kraken Mare was assumed for the design). The sub would spend 20 days at the interface between Kraken Mare and Ligeia Mare for clues to the drainage of liquid methane into the currently predicted predominantly ethane Kraken Mare. During an extended 90 day mission it would transit the throat of Kraken (now 'Seldon Fretum') and perform similar explorations in other areas of Kraken Mare. Once this half year of exploration is completed the submarine could be tasked to revisit points of interest and perhaps do a complete sonar mapping of the seas. All in all, the submarine could explore over 3,000 km (1,864 mi) in its primary mission at an average speed of 0.3 m/s.

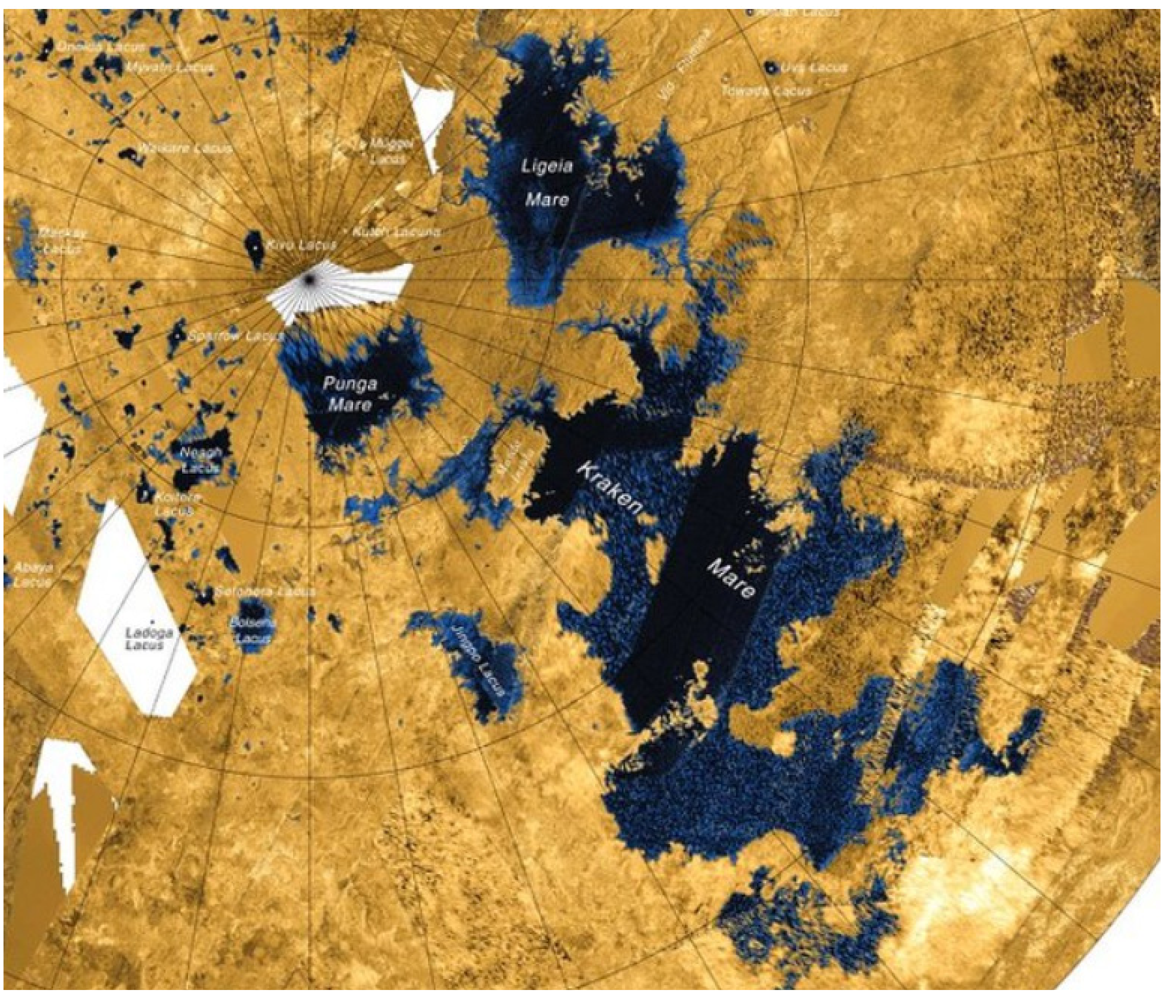
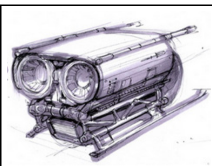
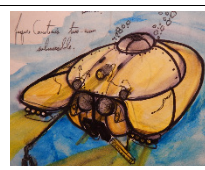
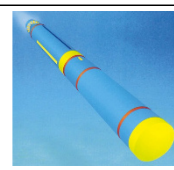
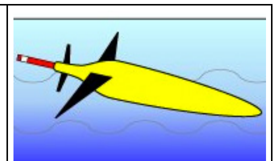


Figure 1.1.—Titan’s Seas or Mare in the Northern Hemisphere.

Focus of this Phase-1 study was on the completely new extraterrestrial, cryogenic submarine so the launch and delivery systems were only notional. A preliminary trade matrix was developed to explore the possible shapes of the submarine based on terrestrial experience, science needs and the added challenges of launching and encapsulating the submarine in an aeroshell. Table 1.1 shows the top level advantages and disadvantages of current terrestrial designs for the Titan Sub mission requirements. While sea gliders have shown to be able to transit great distances with very little power (sinking and gliding with wings and then resurfacing using a ballast system) a science requirement for hovering and in-situ sampling would be difficult for such a vehicle. Due to the size of the seas (1000's of kilometers) the Titan Sub would need to be an efficient cruiser which excludes the Remotely Operated Vehicle (ROV) and diving saucer options. Unfortunately, the length of the torpedo shaped submarine (sized due to required specific weight—it needs to float and sink along with its required power and science instrument mass) would be too large for state of the art (SOA) 4.5 m aeroshells. While larger button shaped aeroshells can be built they would be too large for the 5 m launch vehicle fairing. This last challenge required new options for the aerodescent system.

The downselected torpedo shape of the vehicle needs a new entry/descent approach. While inflatable aeroshells might also work, a lifting body (based on the proven X-37B design) was chosen to hold the submarine through launch and support it through cruise with thermal, communications, propulsion, and navigation (Figure 1.2). The lifting body would then slow the submarine through Titan aeroentry, glide to the proper touchdown point, and perform a soft landing on the surface of Kraken Mare. The Space Shuttle Orbiter was assessed for emergency water landing capability in the 1970s. The Titan Sub's aerovehicle would touch down on Kraken Mare in a similar manner. At some point in the landing sequence, the backshell would be separated from the aerovehicle, the submarine separated and the lifting body allowed to sink. This descent and delivery concept (along with other alternatives) will be explored in detail as part of a Phase II study.

TABLE 1.1.—ADVANTAGES AND DISADVANTAGES OF CURRENT TERRESTRIAL DESIGNS

Driving requirement or attribute	 Remotely operated vehicle	 Diving saucer	 Torpedo shaped unmanned underwater vehicle (UUV)	 Sea glider
Science submerged and surfaced, hovering for in-situ sampling	Yes	Yes	Yes	No
Distance to travel/time: 2000 km/90 days ~ 0.5 m/s Aspect ratio >4:1 reduces power 4 times, smooth exterior	No	No	Yes	Yes
SOA aeroshell limit: <4.5 m, 0.6 specific weight	Yes	Yes	No	No
Communications: DTE needs large antenna area to reduce power, Earth nearer horizon than zenith		Yes Dish integrated into saucer?	Yes Phased array on body?	Yes Phased array on body?

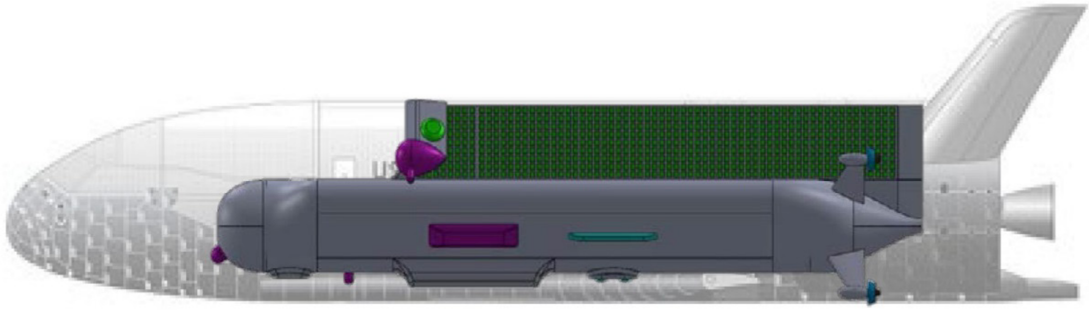


Figure 1.2.—Titan Submarine in Notional X-37 derived lifting body. Acknowledgements: X-37B outline courtesy of Giuseppe De Chiara (used with permission) and http://en.wikipedia.org/wiki/Boeing_X-37#mediaviewer/File:X_37B_OTV-2_01.jpg.

The submarine design faced a great many challenges; some less difficult, some much more difficult than a terrestrial sub. Pressures at depth in a liquid ethane (~ 60 percent the density of water) sea on the smaller world of Titan (~1/5 Earth's gravity) meant that even at the maximum design depth of 1,000 m (3,281 ft) the pressure to be endured was $1/10^{th}$ of that a terrestrial sub would encounter. The sub would need to endure only ~10 bar of pressure at maximum depth on titan, not the 100 bar (10 MPa) pressure it would have to endure in Earth's oceans. This, however also meant that it needed to have a lower average density in order to be positively and neutrally buoyant to operate at the surface and below. Another challenge was that the extremely low temperature (–180 °C) (–292 °F) of the liquid ethane would quickly cool down most terrestrial submarines. The use of isotope power systems (two ~ 500 W Stirling Radioisotope Generators (SRGs)) meant that the submarine had plenty of power and waste heat to keep the internal components at room temperature, with the installation of insulation on the inside of the hull. These isotope systems could not only power the sub for several years beneath the waves of Kraken Mare, but also power the sub and the lifting body during the cruise from Earth to Titan. The power challenges and the thermal requirements led to the use of radioisotope generators. A fission reactor system, while heavier, may also be a feasible power system. An ethane fuel cell, using oxidizers brought from Earth would limit the vehicle to less than a week of operation to say nothing of how the combined vehicles would be powered on the way to Titan.

Communications proved to be a great challenge, but one also solved by use of the isotope power system. While methane has been shown to be radio frequency (RF) transparent, the presumably more-ethane rich composition of Kraken has not yet been shown to be transparent (a topic of ongoing Cassini investigation). As such the submarine, like its terrestrial counterpart will need to surface to communicate. Choice of a 2047 landing date not only ensures continuous lighting conditions for surface imaging, but also allows for direct communications with the Earth. From the Kraken Mare, Earth is never more than 6° from the Sun. As such, it was decided to not use an orbiter (which would have needed an isotope power system for itself) and to double the isotope power system of the submarine to permit communications DTE while the sub is on the surface and then provide extra power for propulsion and science when submerged. Despite the power available, the DTE antenna would need to be large to span the approximately 1.2 billion km (746 million mi) to Earth. Even using geostationary satellites terrestrial submarines only need communicate distances of 36,000 km (22,370 mi) when surfaced.

The concept shown in Figure 1.3 features a 'sail' or 'dorsal fin' above the hull which is a 4- by 0.5-m (13.1- by 1.6-ft) fixed phased array antenna. This antenna can provide greater than 500 bps for two 8 hr Deep Space Network (DSN) communications passes per day. It must operate in a 1.5×10^5 Pa (1.5 bar) nitrogen atmosphere at –180 °C, and then survive up to 1.0×10^6 Pa (10 bar) of –180 °C liquid ethane/ methane. The antenna greatly increases the drag on the sub when submerged but that can be offset using the power not needed for communications (~250 W) for the propeller-based propulsion units (propulsors).

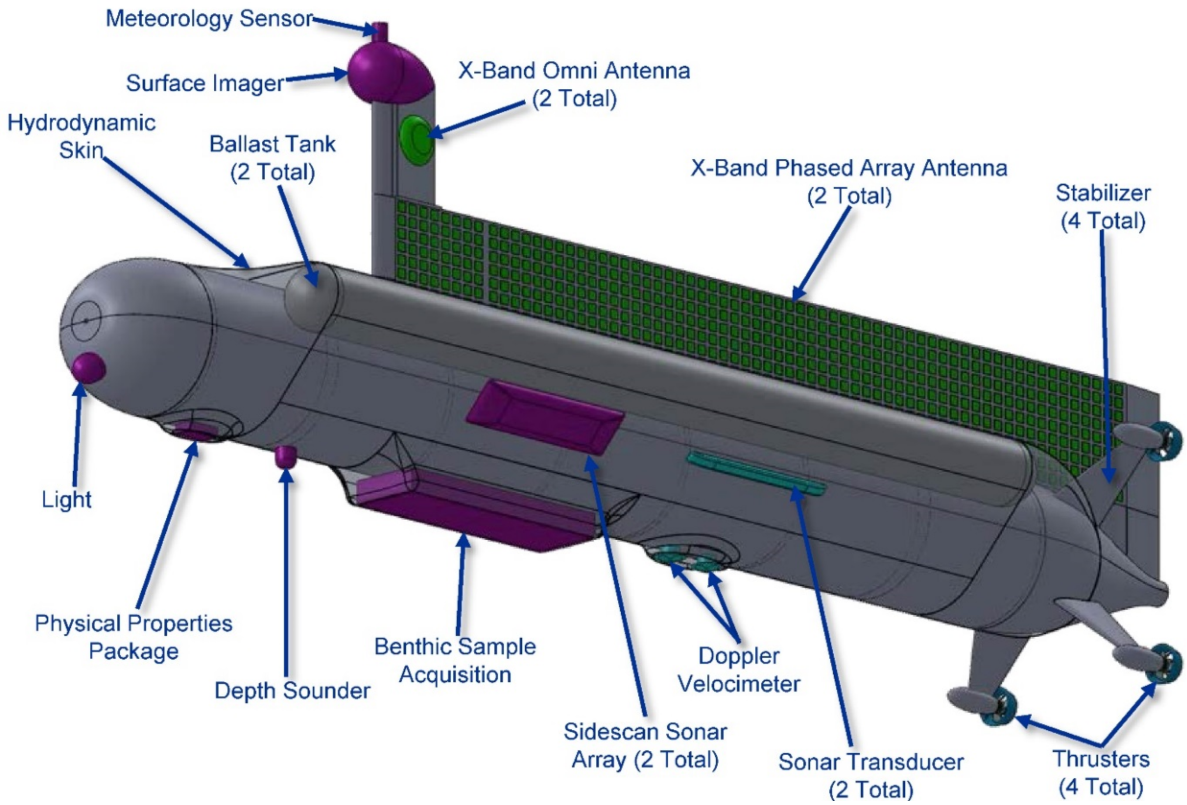


Figure 1.3.—Titan Submarine External Components.

Propulsion using bladed propellers, or propulsors is similar to terrestrial submarines. Four ~100 W motors attached to booms provide propulsion and maneuvering while below the surface. This multiple thruster design was chosen for several reasons:

1. Redundancy to accommodate a motor failure
2. Eliminate the need for actuator/fins
3. Allow for maneuvering the vehicle at low speeds above and below the surface, and
4. Provide easy access to the rear of the hull to load the SRG on the launch pad due to safety and security requirements.

Since drag is lessened on the surface two motors are used during surface cruise. Cavitation on the propellers due to boiling of the ethane is probably not a concern.

The biggest challenge for submarine operations was submerging. Terrestrial submarines use various techniques from diving planes and thrust to ballast tanks filled and then ‘blown’ using compressed atmospheric gases to venture beneath the waves then returns to the surface. While use of thrusters and ‘wings’ to go beneath Kraken is possible, science required neutral buoyancy hovering for submerged imaging and sampling. Using thrusters to offset buoyancy at depth to hover would require about four times the power from the SRGs than is available. Use of a compressed gas ballast system using Titan’s primarily nitrogen atmosphere was found to be infeasible due both to the fact that ethane (and especially methane) can quickly absorb the nitrogen and the nitrogen at –180 °C collapses to a liquid below 4 bar which would limit depths to ~200 m. As such, a boundary between the ballast gas and the ethane as well as use of a gas with a lower liquid point was used. The final system uses cylindrical ballast tanks with

either free floating pistons or bladders pressurized by neon (Ne) brought from Earth and reclaimed after each dive by a compressor during the 16 hr of surface operations. The use of the boundary ‘piston’ meant that the ballast tanks could not be conformal with the pressure hull, following its contours like those of a terrestrial submarine. The positions of the ballast tanks were offset upward to raise the center of buoyancy (CB). The pressure hull and the buoyancy tanks were overwrapped with a composite to create a pseudo v-shaped hull shape to provide better surface stability for antenna pointing and more efficient surface mobility when power was limited.

The final design shown in Figure 1.4 has a mass of approximately 1,386 kg (3,056 lbm) mass. The sub is 6 m (19.7 ft) long with a 0.62 m (2 ft) diameter pressure vessel. External, closed Ne ballast tanks allow for submerging and hovering at as deep as 1,000 m (3,281 ft), and pressures up to 1 MPa (10 bar.)

The major systems of the submarine are summarized below:

- Power: Two 430 W end of life (EOL) SRGs (total power 860 W), loading through rear hatch of aerovehicle/submarine
- Propulsion: Four 100 W motors on booms to provide up to 1.6 m/s (5.2 ft/s) submerged and 0.9 m/s (3 ft/s) surface speeds, as well as differential steering
- Avionics: X-Band communications DTE (~800 bps during 16 hr DSN passes each day surfaced) using 250 W DC, 4- by 0.5-m (13.1- by 1.6-ft) phased array dorsal antenna; Dual X-band omni antennas; Autonomous Command and Data Handling (C&DH) for 16 hr/d surface and 8 hr/d submerged exploration; Navigation using Inertial Measurement Unit (IMU), Sun direction, Earth tracking, liquid velocity Doppler, sonar scanning
- Thermal: Most systems internal warmed by SRG waste heat; 3 cm (1.1 in.) thick aerogel insulation; 300 W/m^2 heat loss thru outer skin; external systems—some science, communications antennas, propulsion, ballast systems must be cryo-capable (–178 °C)
- Mechanical: Pressure vessel capable of withstanding an external pressure of 1×10^6 Pa (10 bar); titanium (Ti) skin and ring stiffeners; internal truss to carry equipment through launch; composite hydrodynamic fairing; dorsal sail to hold phased array antenna and surface science

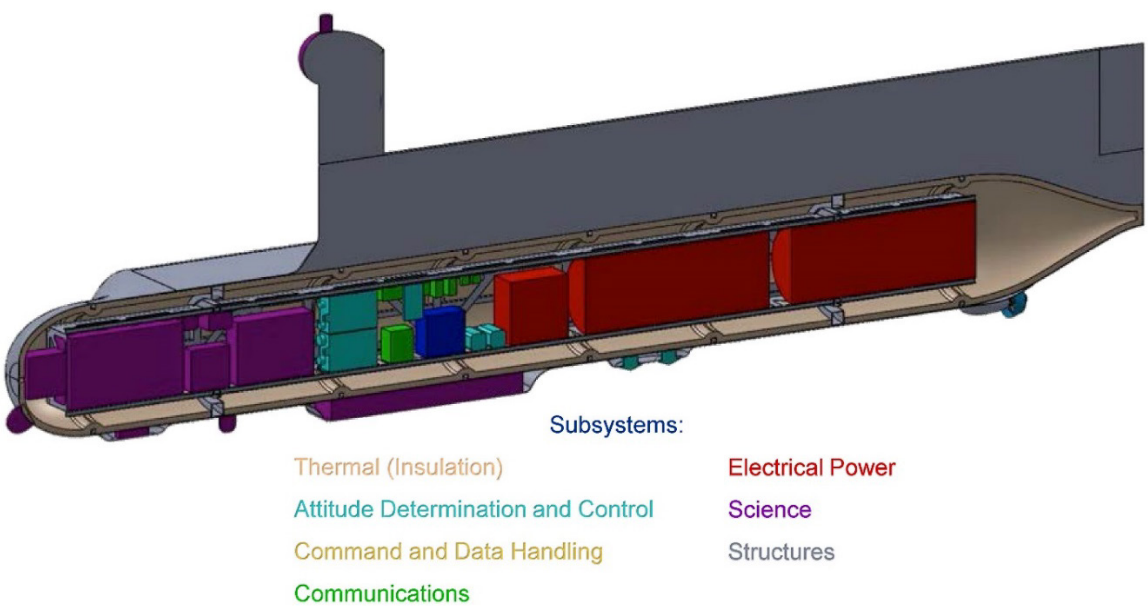


Figure 1.4.—Titan Submarine Internal Components.

The cost estimates for the submarine assuming components are at technology readiness level (TRL) 6 and above (Ref. 1) is around $700M (fiscal year (FY) 14). The technology development, lifting body and launch service would easily take this concept into the flagship cost level.

Based on this design, a Phase II study would seek to refine the submarine design as well as develop the lifting body conceptual design and interplanetary trajectory to get the sub to Titan. Alternate paths of design and technology will be explored along the way (e.g., inflatable aeroshell vs. lifting body). Basic experiments of liquid ethane/methane and nitrogen and Ne will be conducted to prove feasibility.

2.0 Study Background, Assumptions and Approach

2.1 Introduction

Each year the NIAC program asks researchers to propose ideas for space technology or missions that could provide significant scientific advances in the next few decades. In June 2014, NIAC announced 12 winners from the latest proposal activity to be funded for a 9 month study effort. A team of three investigators, Steve Oleson (NASA Glenn Research Center (GRC)), Ralph Lorenz (Johns Hopkins University (JHU) Applied Physics Laboratory (APL)), and Michael Paul (Pennsylvania State University (PSU) Applied Research Laboratory (ARL)), proposed creating a conceptual design for an autonomous submersible to explore the liquid hydrocarbon seas of Saturn's Moon, Titan, using the GRC's COMPASS concurrent engineering team. By addressing the challenges of autonomous submersible exploration in a cold outer solar system environment, a Titan Sub could serve as a pathfinder for even more exotic future exploration of the subsurface water oceans of Europa.

This report is meant to capture the results of the study performed by the COMPASS Team, recognizing that the level of effort and detail found in this report will reflect the limited depth of analysis that was possible to achieve during a concept design session. All of the data generated during the design study is captured within this report in order to retain it as a reference for future work.

2.2 Background

2.2.1 Titan

Titan is the largest moon of Saturn. It is the only natural satellite known to have a dense atmosphere and the only object other than Earth for which clear evidence of stable bodies of surface liquid has been found. The atmosphere of Titan is largely nitrogen with clouds of methane and ethane. The climate—including wind and rain—creates surface features similar to those of Earth, such as dunes, rivers, lakes, seas and deltas, and is dominated by seasonal weather patterns as on Earth.

A summary of relevant information on Titan appears in Table 2.1.

2.2.2 Previous Studies

The unique exploration opportunities afforded by Titan's dense atmosphere, low gravity environment and its seas have stimulated many mission concepts over the years (Ref. 2). These have included landers, airships, hot air balloons, airplanes, helicopters and even hovercraft.

Attention was drawn to exploration of liquid environments on Titan after the discovery of seas in the North Polar Region by Cassini's radar instrument in 2006 (the northern region was then in winter darkness) and the later mapping of these seas. These seas were named by the International Astronomical Union (IAU) Committee on Planetary Nomenclature after mythical sea monsters. They are, in order of ascending size, Punga Mare, Ligeia Mare, and Kraken Mare and became more or less fully-mapped in 2013.

TABLE 2.1.—TITAN SUMMARY INFORMATION

Distance from Sun	1,427,000,000 km (9.54 AU)
Periapsis	1,186,680 km
Apoapsis	1,257,060 km
Semimajor axis	1,221,870 km
Eccentricity	0.0288
Orbital inclination	0.34854° (to Saturn's equator)
Orbital period (Titanic day)	15.95 Earth days
Rotation Period	Synchronous
Mean radius	2,576 km
Mass	1/45 that of Earth
Average density	1.881 times liquid water
Surface temperature	94 K (–180 °C)
Atmospheric pressure at surface	(~1.5 times Earth's)
Atmospheric composition	Nitrogen, methane, argon, ethane
Surface gravity	1.352 m/s^2 (0.14g)

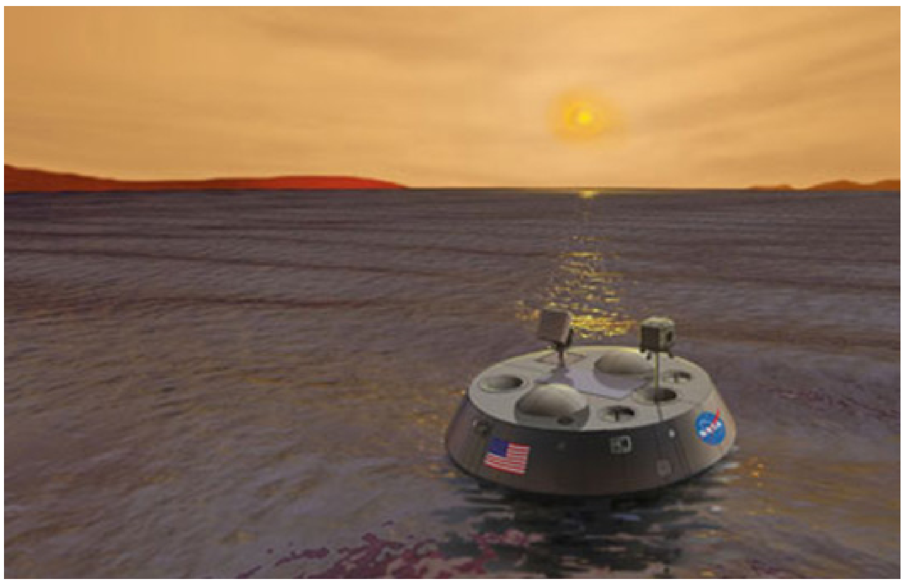


Figure 2.1.—Artist's impression of the Titan Mare Explorer (TiME) Discovery concept.

The joint NASA-ESA 2008-2009 Flagship mission study Titan Saturn System Mission (TSSM) featured a Titan orbiter, a radioisotope-powered Montgolfiere (hot air balloon) and a lake lander. The lake lander was essentially a small version of the Huygens probe, with a 9-hr lifetime limited by its primary battery.

Meanwhile, NASA solicited concepts in 2007 for planetary missions that might be enabled by a SRG, a ~35 kg (77 lbm) power system that would deliver ~120 W_e of electrical output from a ~500 W_{th} radioisotope heat source. One concept submitted was the TiME mission, a capsule which could perform a long duration mission (90 Earth days, corresponding to ~6 Titan days), enabled by both the electrical power and waste heat supplied by this power source (Figure 2.1). This concept was developed further and proposed to the NASA Discovery solicitation in 2010. Of the ~29 proposals submitted, TiME was one of three selected for a Phase A study in 2011. That study resulted in very detailed examination of key practical aspects of exploring Titan's hydrocarbon seas, including entry/descent dispersions, splashdown mechanics, wave height probabilities, tidal circulation, ocean thermodynamics and sonar operations.

TiME (Ref. 3) would have launched in 2016, with arrival at Ligeia Mare in July 2023. Unfortunately, delays in the development of the SRG made selection of the mission for implementation on this schedule impossible. The subsequent Discovery solicitation in 2014 precluded any radioisotope power at all, due to fuel encapsulation schedule challenges.

The arrival date at Titan is critical for an affordable stand-alone mission to Titan's seas, in that direct-to-Earth communication from Titan's seas at high northern latitudes (>65° N latitude) can only be performed when the Earth and the Sun are sufficiently high in the Titan sky. Northern summer solstice occurs in 2017; the equinox is in 2024. After around 2026, Earth is too far south, and thus is too low in the sky or is invisible altogether as seen from Titan's seas.

2.2.3 Titan Seas

Titan (Figure 2.2) is a unique satellite in the solar system in that it has a dense atmosphere (1.5×10^5 Pa (1.5 bar)) which endows Titan with many processes and phenomena familiar to us on Earth. At Saturn's distance from the Sun of 10 AU (1.5×10^9 km; 9.3×10^8 mi), the surface temperature on Titan is 94 K (–290 °F), in part due to the greenhouse warming of methane which makes up a few per cent of the atmosphere (the rest being nitrogen). Ninety-four degrees Kelvin is close to the triple point of methane so it is a condensable greenhouse gas, just like water vapor on Earth. Similarly, methane forms clouds, hail and rain. The methane rain carves river valleys on Titan's surface. The weak sunlight that drives Titan's hydrological cycle results in rain being rare, averaging only a few centimeters per year. These rains are probably expressed as massive downpours depositing tens of centimeters or even meters of rain in a few hours, but interspersed with centuries of drought. In some respects, Titan is to Earth's hydrological cycle what Venus is to its greenhouse effect—a terrestrial phenomenon taken to a dramatic extreme.

Titan is tilted 26° on its spin axis so its climate has significant seasonal forcing, but since it takes 29.5 Earth years to go once around the Sun, its seasons are long. In addition to seasonal rainfall, the annual cycle also manifests in Titan's stratospheric circulation, where wide swings in the abundance of various organic gasses and hazes (produced by the action of ultraviolet light on methane) take place.

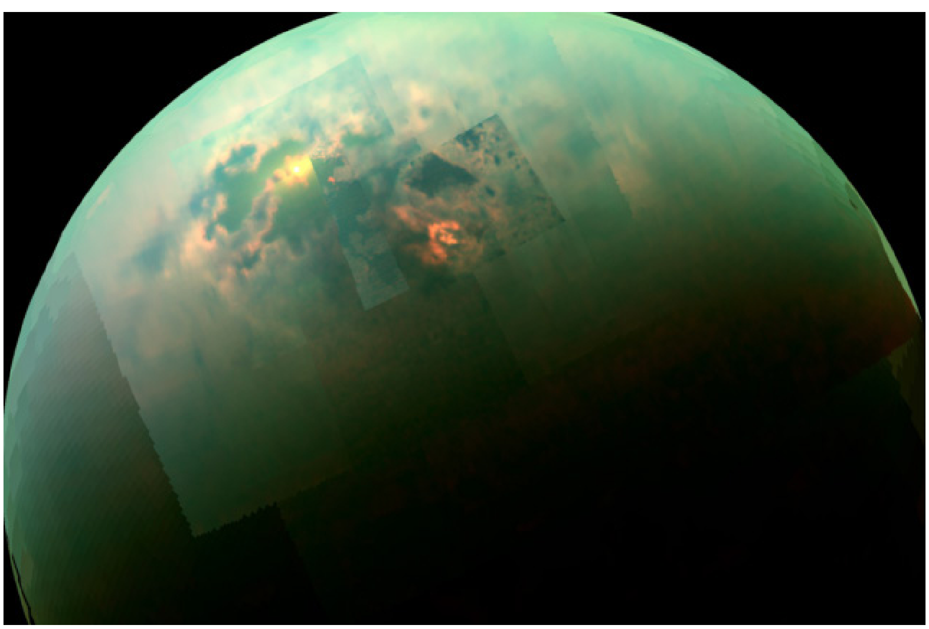


Figure 2.2.—Cassini captures sunlight glinting off of Titan's seas.

These changes are particularly strong at the winter pole, with some analogies to polar stratospheric clouds and the ozone hole dynamics on Earth. Among the gasses produced by photochemistry is ethane, which is also a liquid at Titan conditions, and is also expected to accumulate on the surface.

Although hydrocarbon seas were long speculated to exist on Titan, bodies of standing liquid were only confirmed (in northern winter darkness) by Cassini radar observations in 2006, some 2 yr after the probe arrived in the Saturnian system (Figure 2.3). Hundreds of radar-dark lakes, typically 20 km (12.4 mi) across, were discovered at about 70° N. Latitude. By international convention, lakes on Titan are named after lakes on Earth, while the three seas are named after sea monsters. Ligeia Mare, a 300 to 400 km (186 to 249 mi) wide body, was the first sea to be observed. The smaller Punga Mare is closer to the North Pole, while the giant Kraken Mare sprawls over some 1,000 km (621 mi) towards mid-latitudes.

Strikingly, the southern hemisphere has only one modest body of liquid, Ontario Lacus, about 70- by 250-km (43 to 155 mi). This so far is one of the most-studied lakes, since the south was better illuminated in the 2004 to 2010 time period allowing near-infrared (IR) remote sensing on Cassini to detect ethane.

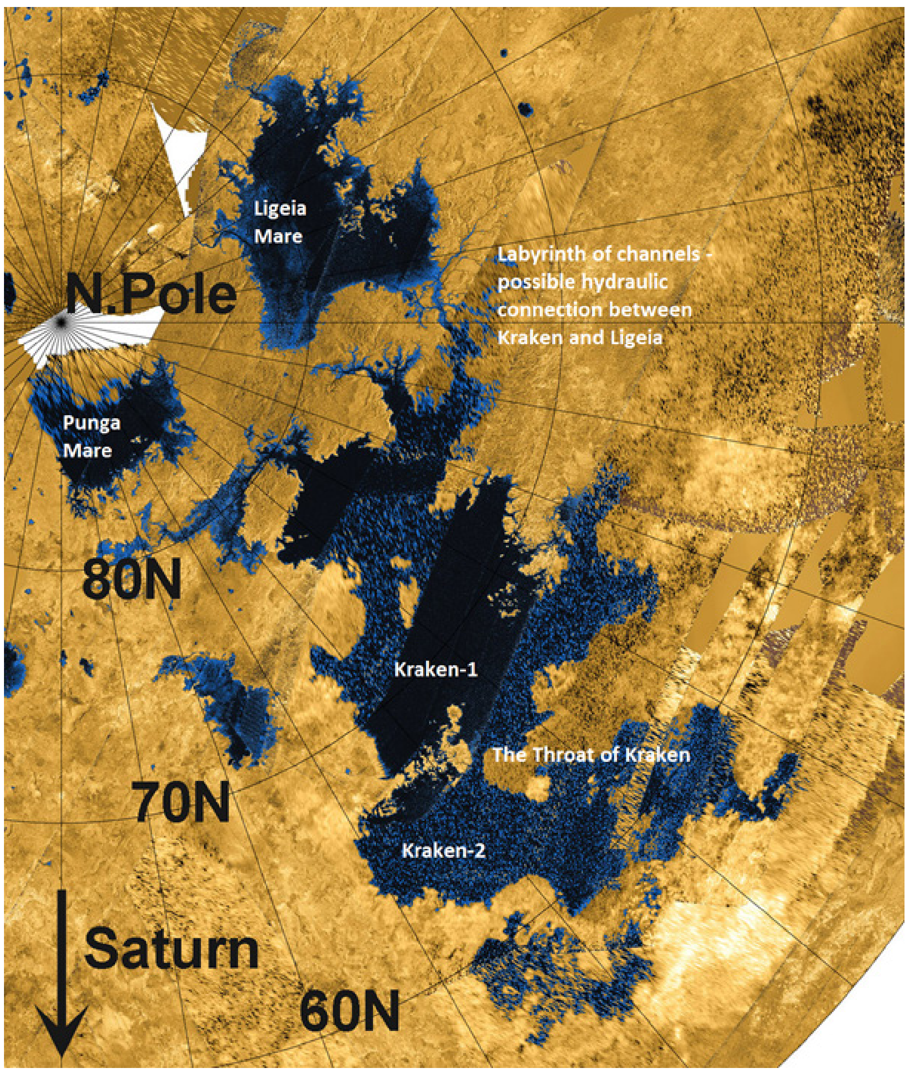


Figure 2.3.—A radar map of Titan's northern Polar Regions. Note that because Titan rotates synchronously with Saturn, the direction toward that planet is fixed (in fact, the sub-Saturn point defines the zero longitude).

Further analysis of the near-IR data suggests that Ontario Lacus may in fact be muddy, and a bright margin is suggestive of a 'bathtub ring' of evaporite deposits. Of course, these are not salts familiar as solutes in terrestrial waters, but some organic analog where differential solubility in an evaporating basin has been preferentially deposited at the shrinking margins. In fact, a comparison between an optically-measured outline and the margins in a radar image some years later suggest that Ontario may have shrunk in extent due to seasonal evaporation and the very shallow regional slopes. Ontario is most likely only a few meters deep.

The preponderance of seas in the northern hemisphere is thought to be the result of the astronomical configuration of Titan's seasons in the current epoch, which has the result that the northern summer is less intense but longer in duration than that in the south. This results in a longer 'rainy season' in the north, such that methane and ethane accumulate there. This seasonal configuration lasts several tens of thousands of years, much like the Croll-Milankovich cycles that play a part in the Earth's ice ages and the Martian polar layered terrain. This picture of a drying south and accumulating north is consistent with the submerged or ria coastlines of Punga-Ligeia-Kraken which suggest valleys being flooded by rising sea levels, and with the kidney-shaped outline, shallow (and possibly declining) depth of Ontario Lacus in the south.

One of the most striking observations in the near-IR is of the Sun glinting off the surface of the lakes (Figure 2.4). In fact this, like the low radar reflectivity, told us that the roughness of the lakes must be exceptionally low, but it is a very iconic observation. The lake was appropriately named Jingpo Lacus named after the 'Mirror Lake' in China.

The notion of extraterrestrial seas offers great possibilities for thought experiments and for teaching. In fact, the liquid methane and ethane that dominate the seas composition are handled routinely on Earth, at the temperatures encountered on Titan, by the liquefied natural gas (LNG) industry. The density of ethane is about 2/3 that of water, and the viscosity is rather similar, depending on temperature. Methane is a little less dense and rather less viscous. Many dissolved constituents (higher hydrocarbons, nitriles) may also be present and would increase the density, viscosity and dielectric constant. It is conceivable that compositional or thermal stratification may occur depending on how tides and wind-driven currents stir Kraken's depths.

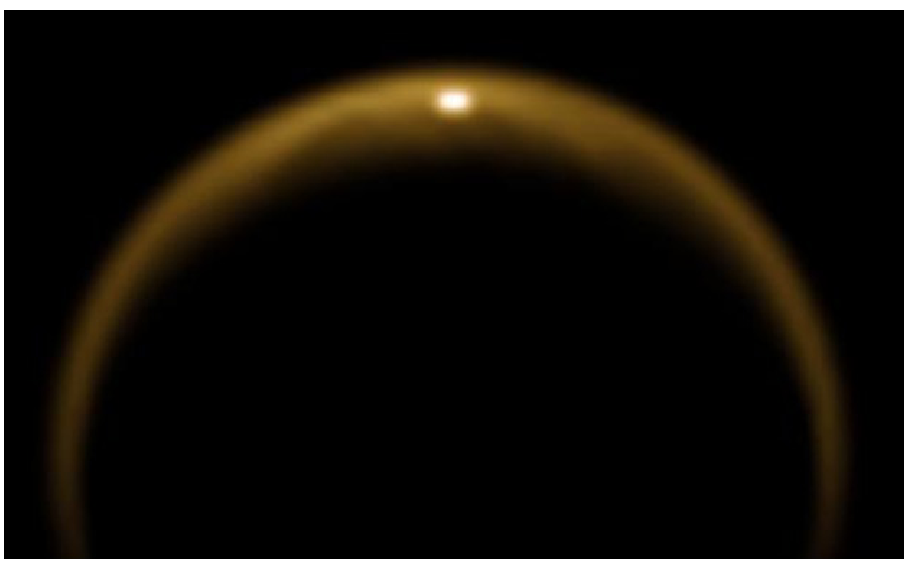


Figure 2.4.—The glint of near-IR light from the mirror-smooth surface of Jingpo Lacus.

The tidal forces on Titan are strong, given Saturn's large gravity, but change only slowly due to the 15.945 Earth day orbit period. Titan is gravitationally locked to its primary, pointing the same face towards it so the tidal bulge is near-fixed, varying only by ~9 percent over the day due to the eccentric orbit. The slow period means that resonant tides (like those in our Bay of Fundy) are unlikely. Nonetheless, tidal amplitudes of a few tens of centimeters have been calculated for Kraken, with current speeds of a few centimeters per second.

The possibility of waves on Titan's seas was recognized during the formulation of the Cassini mission, and the Huygens probe was equipped with tilt sensors to measure any motion on waves should the probe survive splashdown on a liquid surface (since the surface was completely unknown, surface operations were not guaranteed). In Titan's low gravity ($a_g = 1.35$ m/s^2 (4.4 ft/s^2), like that of our Moon), propagation of a wave of a given wavelength is rather slow compared with Earth.

The remarkable flatness of Titan's seas posed a puzzle. Why, in Titan's low gravity and thick atmosphere, should the seas not have waves if the hydrocarbon liquids behave like water? One possibility is that winds are too light (yet it is evidently strong enough sometimes to form sand dunes). Another possibility is that the seas may be viscous enough to damp waves. Although waves have yet to be observed, the question of wave height is of interest for shoreline erosion effects, and in particular for the design of vehicles that might float on the surface of the seas. Recent work found that the threshold wind speed for capillary wave generation should be ~0.4 m/s (1.3 ft/s) for methane-rich (low viscosity) seas, or ~0.6 m/s (2 ft/s) for ethane-rich seas (viscosity similar to water). Such speeds have likely not been encountered during the Cassini mission in either hemisphere, although in coming years as we move towards northern summer solstice, Global Circulation Models (GCM) predict a rising probability that winds over Kraken or Ligeia may freshen enough to generate waves that are observable via the Sun-glint pattern on the sea surface or by its radar reflectivity. Once capillaries form, they can grow and become progressively larger gravity waves. Given GCM predictions of maximum ~2 m/s (6.6 ft/s) in summer, the significant wave height is expected to reach ~80 cm (2.6 ft) or so, therefore shoreline erosion and beach processes are possible on Titan. Sediment transport, given the low density contrast between ice bedrock and hydrocarbon liquid, and the low gravity should be readily mobilized in Titan's seas.

Since the relative humidity of methane on Titan is only ~50 percent, a body of pure methane cannot persist indefinitely on Titan's surface since it is not in thermodynamic equilibrium. The evaporation rate has been estimated at up to 1 m/yr (3.3 ft/yr), using terrestrial empirical transfer coefficients. This is strongly dependent on wind speed. The evaporation rate is composition-dependent, in that the saturation vapor pressure of ethane is very low. Ethane acts to suppress the partial pressure of methane above mixed-composition seas (much as syrup will evaporate in a kitchen much more slowly than water), so Titan's air-sea interactions have some complexities not usually faced on Earth. While ethane probably migrates only over long (>10,000 yr) periods, evaporation and precipitation of methane may be much more like terrestrial weather, with hourly and seasonal changes as well as longer-term effects. In fact, transient surface darkening has been observed at low latitudes on Titan in association with methane clouds, followed by brightening, suggesting that shallow flooding occurred, followed by evaporation. The hydrological cycle on titan is clearly active today.

Titan's landscape, atmosphere and climate system have many parallels with Earth, with the added interest of the astrobiological implications of Titan's prebiotic chemistry and rich inventory of organics. Thus Titan remains an important target for future exploration.

2.3 Science Instruments

2.3.1 Science Overview

The scientific goals of the Titan Submarine derive from those developed for the 2007 Titan Explorer Flagship study (Ref. 4) and are shown in Table 2.2. Although the seas on Titan were discovered only

during that study, the objectives were broad enough to remain community-endorsed in subsequent studies such as TSSM and the Decadal Survey.

2.3.2 Science Requirements

More specifically, the scientific goals of the Titan Submarine shown in Table 2.3 are the same as those of the Decadal Survey lake lander, but modified to embrace the growing interest in the diverse shorelines of Titan's seas which can be explored by a mobile sea platform, and to recognize the paleoclimate study potential in the seabed sediments.

TABLE 2.2.—THE SCIENTIFIC GOALS OF THE 2007 TITAN EXPLORER FLAGSHIP STUDY

Exploring an Earthlike Organic-Rich World	
OBJECTIVE 1: Titan: An Evolving Earthlike System ▪ How does Titan function as a system? How do we explain the similarities and differences among Titan, Earth, and other solar system bodies? To what extent are these controlled by the conditions of Titan's formation and to what extent by the complex interplay of ongoing processes of geodynamics, geology, hydrology, meteorology, and aeronomy in the Titan system?	OBJECTIVE 2: Titan's Organic Inventory: A Path to Prebiological Molecules ▪ What are the processes responsible for the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its subsurface water ocean? How far has this chemical evolution progressed over time? How does this inventory differ from known abiotic organic material in meteorites and biological material on Earth?

TABLE 2.3.—SCIENTIFIC GOALS OF THE TITAN SUBMARINE

	Objective	Heritage	Contributing Instruments
A1	Explore the morphology and character of the seabed to understand the history of the basin and sediment deposits	New	Depth Sounder (DS), Sidescan Sonar (SS), Undersea Imager (UI)
A2	Explore the morphology of shoreline features to understand Titan's geological history	TE 2007/TSSM/TiME	Surface Imager (SI)
A3	Measure sea-surface meteorology to constrain larger-scale weather activity and air-sea exchange	TSSM/Decadal/TiME	Meteorology Package (MET), Navigation
A4	Measure sea physical characteristics (currents, waves, turbidity) and their variations over space and time	TSSM/Decadal/TiME	Physical Properties Package (P3), SI, Navigation, (UI, DS)
A5	Measure horizontal and depth variations of major constituents to constrain exchange and mixing processes	Decadal (option)	Infrared Spectrometer (IRS), P3, (Chemical Analysis Package (CAP)), (DS)
B1	Measure trace organics in sea, with emphasis on prebiotic chemistry	TSSM/Decadal/TiME	CAP, IRS
B2	Measure isotopic ratios of noble gases and organics to constrain origin and evolution of Titan	TSSM/Decadal/TiME	CAP
B3	Measure composition of seabed material (best effort)	Decadal /New	BAS, CAP

2.3.3 Instruments

The science requirements drove the strawman payload listed in the Table 2.4. The chemical composition of the seas (and any sediments) is a complex topic, as evidenced in the discussion of solid composition analysis in Reference 4. We have not specified the internal makeup of the CAP. It might comprise a sample volatilization system coupled to a Gas Chromatograph Mass Spectrometer (GCMS), tandem mass spectrometry (MS-MS) or similar analyzer for broad chemical characterization and isotopic measurement. Additional possibilities include Raman, fluorescent or other techniques for specific species of astrobiological interest. The overall resource envelope is patterned after the Sample Analysis at Mars (SAM) package on Mars Science Laboratory (MSL) Curiosity.

TABLE 2.4.—SCIENCE INSTRUMENTS FOR THE TITAN SUBMARINE

	Instrument	Technique	Rationale	Requirements	Basis
Floor	Chemistry Analysis Package (CAP)	Liquid sample acquisition system coupled to multiple analytic instruments (nominally GCMS)	Measure bulk and trace constituents of sea at different locations and depths	Inlet isolated from heat source; 40 kg, 80 W when sampling (2 hr; once per 2 d)	Curiosity/SAM
	Surface Imager (SI)	Panoramic charged-couple device (CCD) imager (gimballed) on upper structure	Observe sea surface, shoreline geomorphology, clouds, atmospheric optics	Topside mount, 1 m above sea surface; 4 kg including housing; 10 W when imaging (2 hr/d)	MER Pancam
	Depth Sounder (DS)	Single down-looking acoustic sounder	Low frequency (10 to 20 kHz) to measure depth to bottom, possibly detect layers, bubbles, etc.	Nadir view; 0.5 kg 2 W continuous	TiME MP3, commercial fish finders
	Meteorology Package (MET)	Pressure, temperature, wind speed and direction, methane humidity on surface	Record meteorological variability, forcing of air/sea exchange	Topside mount, 1 m above sea surface, desirably away from heat source; 3 kg 6 W continuous	TiME MP3, Pathfinder ASI/MET, terrestrial field instruments
	Physical Properties Package (P3)	Sea temperature, speed of sound, dielectric constant and turbidity	Structure of liquid column (stratification), suspended sediment, air/sea exchange, local variations in bulk ethane/methane	Isolated from heat source; 2 kg; 6 W continuous	TiME MP3/ Huygens Surface Science Package (SSP)
Baseline	Sidescan Sonar (SS)	Side-looking acoustic imaging array	Acoustic imaging of seabed morphology	Bottom/side view; 10 W when operating; 8 hr/d	Terrestrial UUV
	Undersea Imager (UI)	Medium-field CCD imager equipped with multicolor illuminators	Optical imaging of seabed (combine with SI if vehicle orientation permits)	Forward view; 3 kg including housing; 20 W when imaging; 1 hr/d	Curiosity Mars Hand Lens Imager (MAHLI)
	Benthic Sample Acquisition (BSA)	Grinding/suction system to ingest solid or semi-solid seabed materials	Deliver seabed sediments to CAP instrument	Forward/lower view; 5 kg; 50 W when operating 1 hr/2 d	Phoenix rasp plus suction pump
	Infrared Spectrometer (IRS)			8 kg; 20 W; 2 hr/d	Miniature Thermal Emission Spectrometer (miniTES), laboratory instruments
Engineering	Navigation Systems (NAV)	Pressure depth gauge, IMU, plus Doppler/Delta Differential One-way Ranging (DOR) radio measurements	Infer ocean currents	Bookkept under GN&C System	Various

It is recognized that such an elaborate analysis system may have a finite number of samples that can be examined, due to finite sample holders, analyte or carrier gas supply, pump saturation, etc. Thus a system capable of measuring broad composition (ethane, methane, propane etc.) more or less continuously is also included. This is notionally a near-IR or mid-IR absorption spectrometer, guiding light from an internal incandescent lamp source through the hull via fiber optic light guides across a sample path near the hull. Other instrument architectures could be envisioned. Although in principle physical properties such as dielectric constant or speed of sound can be estimated knowing the composition, there is some convenience and robustness to determining these properties directly (e.g., for reduction of DS measurements one needs a speed of sound measurement) and these simple sensors are implemented on the P3, which is patterned after the Huygens SSP instrument.

Surface meteorology is an important science goal for Titan overall, but is a somewhat secondary priority for a submarine. A methane humidity measurement, pressure, temperature and wind speed are measured from a sensor package on a mast as high as possible above the waterline. This is done because it is recognized that wind and temperatures, and possibly humidity measurements, may be influenced by the vehicle, its motion and/or its heat output.

The function of the SI is to inspect the shoreline, observe the sea surface for floating material, Langmuir rolls, waves, etc., and to observe the atmospheric scattering and detect clouds and rain. In order to have a horizon of about 2 km (1.2 mi), this camera must be mounted 1 m (3.3 ft) above the waterline. The SI is collocated on a mast with the MET which is located above it. This camera should be capable of panoramic views, either via optics, multiple apertures, or a gimbal. A separate down-looking camera with illuminators is carried on the forward end of the sub for observation of the seabed.

Several acoustic systems are carried, with somewhat different functions. The DS is a powerful nadir-pointed system, designed to measure the depth to the seabed (from the surface or below, to a nominal depth of 1 km (0.6 mi)). It can also detect possible layers in the sea, and in the seabed. The side-looking sonars have larger transducer arrays to yield a narrow fan beam on either side of the vehicle for high-resolution imaging of the seabed morphology. Nominally, this system may work to a depth of 100 m (330 ft). At greater depths, mapping may be done while submerged. An additional sensor, not part of the science payload but rather the GN&C system is a Doppler velocity gauge, to determine drift or speed relative to the seabed to reduce navigation errors.

Provision of a system to obtain samples of seabed sediments is noted (BSA) although we have not considered the details of such a system. This system could be an arm/drill type of sampler, or even a tethered or untethered sub-vehicle.

The science instrument list for the Titan submarine is shown in Table 2.4, and the MEL for the science instruments is shown in Table 2.5.

2.4 Study Assumptions and Approach

Given the limited funds from the NIAC Phase I award, the conceptual design effort focused on the Titan submarine and notionally touched on Titan descent, aeroshell and cruise systems. These would be further assessed as part of a Phase II study.

The submarine's design and its mission profiles were driven by the science requirements. Science to be performed is directly traceable to the Decadal Survey requirements for solar system missions. Meeting these science requirements with a submarine designed to survive the exotic environment on Titan lead to it being a Discovery, New Frontiers or Flagship class mission.

The assumptions and requirements about the titan submarine, including those that were known prior to starting the COMPASS design study session, are shown in Table 2.6. This table gathers the assumptions and requirements and calls out trades that were considered at the beginning of the design

study, and off-the-shelf (OTS) materials that were used wherever possible. Figure 2.5 illustrates the top-level design considerations and trades performed during the execution of the study.

TABLE 2.5.—SCIENCE INSTRUMENT MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Science Payload	--	-----	91.0	30.0	27.3	118.3
Floor	--	-----	50.0	30.0	15.0	65.0
CAP	1	40.0	40.0	30.0	12.0	52.0
SI	1	4.0	4.0	30.0	1.2	5.2
DS	1	0.5	0.5	30.0	0.2	0.7
MET	1	3.0	3.0	30.0	0.9	3.9
P3	1	2.0	2.0	30.0	0.6	2.6
Light	1	0.5	0.5	30.0	0.2	0.7
Baseline	--	-----	41.0	30.0	12.3	53.3
SS	2	5.0	10.0	30.0	3.0	13.0
UI	1	3.0	3.0	30.0	0.9	3.9
BSA	1	20.0	20.0	30.0	6.0	26.0
IRS	1	8.0	8.0	30.0	2.4	10.4

TABLE 2.6.—ASSUMPTIONS AND STUDY REQUIREMENTS

Item	Requirements / Assumptions	Trades
Top-Level	Autonomous submarine to explore seas of Titan: Kraken North (90 d), Kraken South (90 d), option for Ligeia (90 d) FOMs: science data return, area covered/time, Single fault tolerant	Which lakes, range, duration, surface vs submerged science objectives
System	Identify new technologies, ~2040 launch year, ~ 2047 splashdown (mass growth per ANSI/AIAA R-020A-1999 (add growth to make system level 30 percent)	
Mission, Ops, GN&C	X-37 shaped aeroshell descent, surface landing, Lands/deploys during sunlit/ Earth viewable summer at northern pole. Investigates using sonars, chemical analyzers, spectrometers, imagers. Explores for 90 d (base mission) Kraken 1, then 90 d Kraken 2, then option to explore Ligeia (90 d). 1 m/s submerged speed	Earth, Venus, Jupiter flybys SOA 4.5 m aeroshell vs long, lifting body aeroshell vs inflatable aeroshell
Launch Vehicle (LV)	Atlas 5 Launch Loads: Axial SS ± up to 5 g, Lateral ± 2g	
Mobility/ buoyancy	~150 to 350 W electric driven propellers (surface – submerged), 1 m/s, external ballast tanks for diving/surfacing, insulated submarine pressure vessel set at 150 psi xenon (Xe) to offset 1 km ethane lake pressures, pumped ballast tanks using high pressure Ne and piston arrangement for 1000 m max depth	Propeller type, # placement, waste heat jets (not enough heat), waste heat activated ballast tanks (not enough heat), back pressure gas (N_2 from atmosphere) or mechanical bellows using stored/reused gas
Power	Two 430 W EOL SRGs (~3600 W waste heat)	Chemical fuel cell (using oxidizer carried ~2 kW-hr/kg, ~ 1 wk operation for equivalent SRG mass), thermoelectric generators (>10 kW waste heat)
Avionics/ Communications	Autonomous vehicle, DTE communications using 4x.5m phased array antenna, 400 W dc, 500 bps through DSN, 16 hr/d while surfaced	Orbiter relay
Thermal and Environment	3 cm thermal aerogel insulation, waste heat through sub walls 300 W/m^2, internal temperature 20 °C	Thickness of insulation vs radiator size, effect of nitrogen escaping from ethane solution next to hot skin TBD
Mechanisms	Separation Systems, camera/MET package deployment, camera pointing, sediment probe	How to separate from lifting body
Structures	~ 5 g axial loads, 2 g lateral, Ti pressure vessel	
Cost	Flagship	
Risk	Major Risks: unknown sea depth/debris	

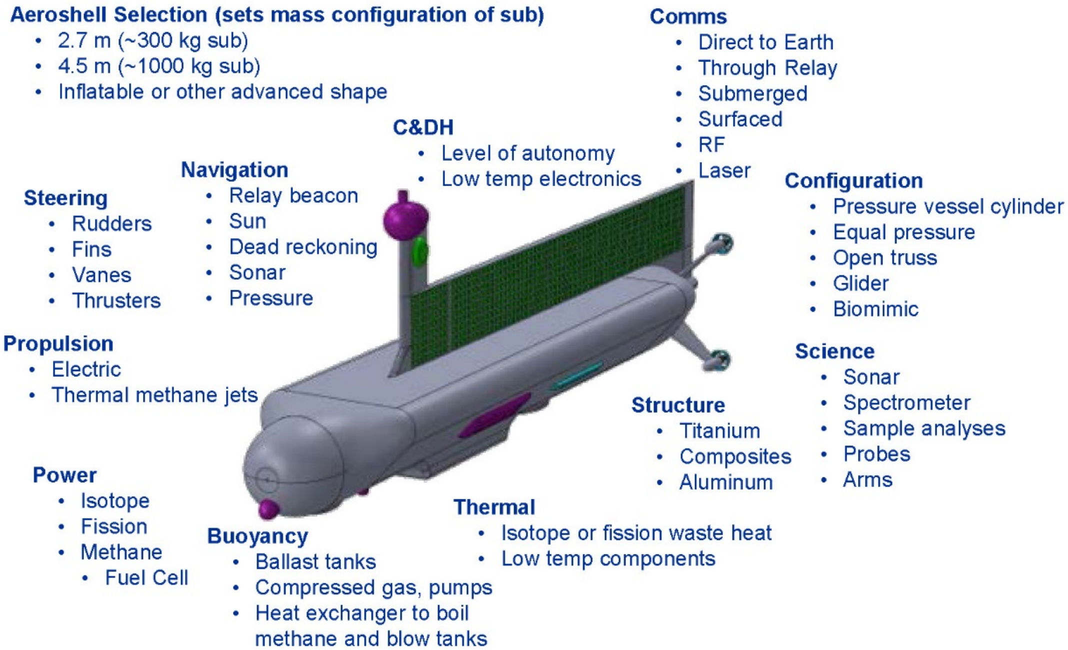


Figure 2.5.—Titan Submarine Trades.

2.5 Study Summary Requirements

2.5.1 Figures of Merit (FOMs)

The relative merit of the conceptual design was judged against:

- The amount of science data return from Titan
- Maximizing the surface mission specifics on Titan:
  - Voyage duration
  - Distance covered
  - Depth reached by the sub
- Mass, as always, is a FOM. Minimizing the mass reduces LV size and cost, and reduces trip time to Titan
- Cost: For the first design it was determined to allow a flagship cost to investigate the amount of science possible.
- Risk: While already requiring long time delays for communications, submersed operations will require some sort of autonomous surfacing capability, similar to Earth UUVs, to return to the surface if anomalies are encountered.

2.6 Growth, Contingency, and Margin Policy

The COMPASS Team follows a standard set of definitions for mass, growth and contingency for each study executed by the team. Those definitions appear below, followed by a graphical representation in Figure 2.6.

Mass	*The measure of the quantity of matter in a body.*
Basic Mass (aka CBE Mass)	*Mass data based on the most recent baseline design. This is the bottoms-up estimate of component mass, as determined by the subsystem leads.*

Note 1: This design assessment includes the estimated, calculated, or measured (actual) mass, and includes an estimate for undefined design details like cables, multi-layer insulation (MLI), and adhesives.

Note 2: The mass growth allowances (MGA) and uncertainties are not included in the basic mass.

Note 3: COMPASS has referred to this as current best estimate (CBE) in past mission designs.

*Note 4: During the course of the design study, the COMPASS Team carries the propellant as line items in the propulsion system in the Master Equipment List (MEL). Therefore, propellant is carried in the basic mass listing, but MGA is **not** applied to the propellant. Margins on propellant are handled differently than they are on dry masses.*

CBE Mass *See Basic Mass.*

Dry Mass *The dry mass is the total mass of the system or spacecraft (S/C) when no propellant is added.*

Wet Mass *The wet mass is the total mass of the system, including the dry mass and all of the propellant (used, predicted boil-off, residuals, reserves, etc.). It should be noted that in human S/C designs the wet masses would include more than propellant. In these cases, instead of propellant, the design uses Consumables and will include the liquids necessary for human life support.*

Inert Mass *In simplest terms, the inert mass is what the trajectory analyst plugs into the rocket equation in order to size the amount of propellant necessary to perform the mission delta-Velocities (ΔVs). Inert mass is the sum of the dry mass, along with any non-used, and therefore trapped, wet materials, such as residuals. When the propellant being modeled has a time variation along the trajectory, such as is the case with a boil-off rate, the inert mass can be a variable function with respect to time.*

Basic Dry Mass *This is basic mass (aka CBE mass) minus the propellant or wet portion of the mass. Mass data is based on the most recent baseline design. This is the bottoms-up estimate of component mass, as determined by the subsystem leads. This does not include the wet mass (e.g., propellant, pressurant, cryo-fluids boil-off, etc.).*

CBE Dry Mass *See Basic Dry Mass.*

MGA *MGA is defined as the predicted change to the basic mass of an item based on an assessment of its design maturity, fabrication status, and any in-scope design changes that may still occur.*

Predicted Mass *This is the basic mass plus the mass growth allowance for to each line item, as defined by the subsystem engineers.*

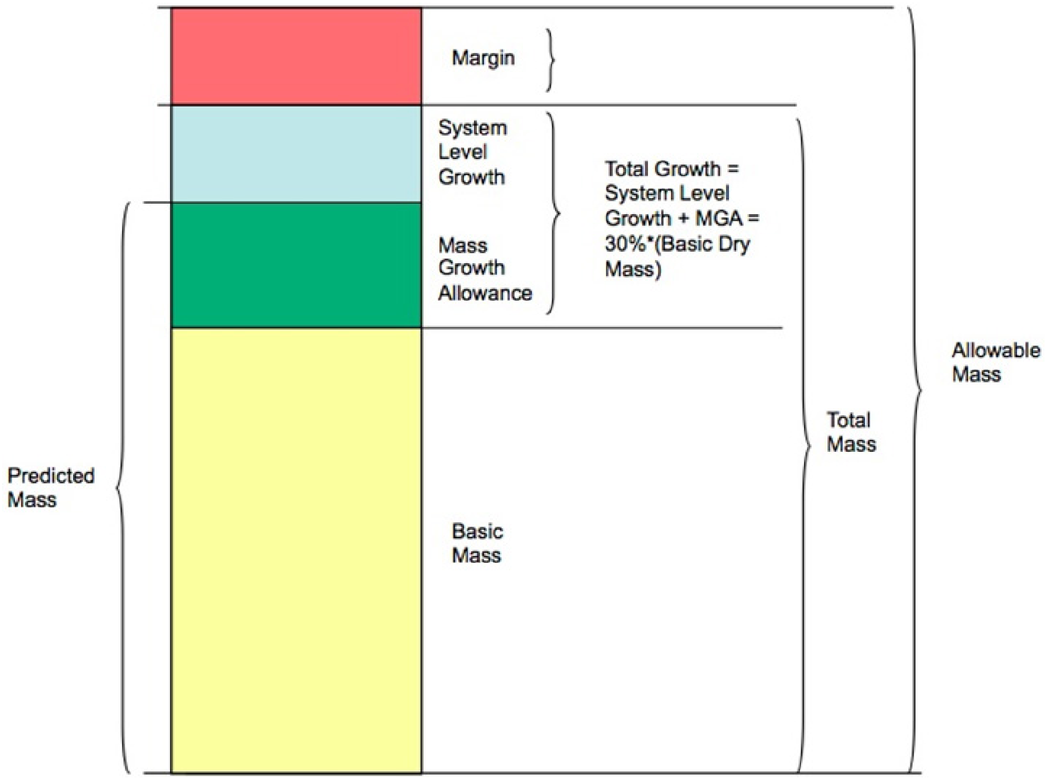
Note: When creating the MEL, the COMPASS Team uses Predicted Mass as a column header, and includes the propellant mass as a line item of this section. Again, propellant is carried in the basic mass listing, but MGA is not applied to the propellant. Margins on propellant are handled differently than they are handled on dry masses. Therefore, the predicted mass as listed in the MEL is a wet mass, with no growth applied on the propellant line items.

Predicted Dry Mass *This is the predicted mass minus the propellant or wet portion of the mass. The predicted mass is the basic dry mass plus the mass growth allowance as*

the subsystem engineers apply it to each line item. This does not include the wet mass (e.g., propellant, pressurant, cryo-fluids boil-off, etc.).

Mass Margin (aka Margin)	*This is the difference between the allowable mass for the space system and its total mass. COMPASS does not set a Mass Margin, it is arrived at by subtracting the Total mass of the design from the design requirement established at the start of the design study such as Allowable Mass. The goal is to have Margin greater than or equal to zero in order to arrive at a feasible design case. A negative mass margin would indicate that the design has not yet been closed and cannot be considered feasible. More work would need to be completed.*
System-Level Growth	*The extra allowance carried at the system level needed to reach the 30 percent aggregate MGA applied growth requirement.* *For the COMPASS design process, an additional growth is carried and applied at the system level in order to maintain a total growth on the dry mass of 30 percent. This is an internally agreed upon requirement.* *Note 1: For the COMPASS process, the total growth percentage on the basic dry mass (i.e., not wet) is:* *Total Growth = System Level Growth + MGA*Basic Dry Mass* *Total Growth = 30 percent* Basic Dry Mass* *Total Mass = 30 percent*Basic Dry Mass + basic dry mass + propellants.* *Note 2: For the COMPASS process, the system level growth is the difference between the goal of 30 percent and the aggregate of the MGA applied to the Basic Dry Mass.* *MGA Aggregate percent = (Total MGA mass/Total Basic Dry Mass)*100* *Where Total MGA Mass = Sum of (MGA percent*Basic Mass) of the individual components* *System Level Growth = 30 percent* Basic Dry Mass – MGA*Basic Dry Mass = (30 percent – MGA aggregate percent)*Basic Dry Mass* *Note 3: Since CBE is the same as Basic mass for the COMPASS process, the total percentage on the CBE dry mass is:* *Dry Mass total growth +dry basic mass = 30 percent*CBE dry mass + CBE dry mass.* *Therefore, dry mass growth is carried as a percentage of dry mass rather than as a requirement for LV performance, etc. These studies are Pre-Phase A and considered conceptual, so 30 percent is standard COMPASS operating procedure, unless the customer has other requirements for this total growth on the system.*
Total Mass	*The summation of basic mass, applied MGA, and the system-level growth.*
Allowable Mass	*The limits against which margins are calculated.* *Note: Derived from or given as a requirement early in the design, the allowable mass is intended to remain constant for its duration.*

Table 2.7 expands definitions for the MEL column titles to provide information on the way masses are tracked through the MEL and used in the COMPASS design sessions. These definitions are consistent with those above in Figure 2.6 and in the terms and definitions. This table is an alternate way to present the same information to provide more clarity.



(Basic = bottoms-up estimate of dry mass) (MGA = applied per subsystem line item)

Figure 2.6.—Graphical illustration of the definition of basic, predicted, total and allowable mass.

TABLE 2.7.—DEFINITION OF MASSES TRACKED IN THE MEL

CBE mass	MGA growth	Predicted mass	Predicted dry mass
Mass data based on the most recent baseline design (includes propellant)	Predicted change to the basic mass of an item phrased as a percentage of CBE dry mass	The CBE mass plus the MGA	The CBE mass plus the MGA — propellant
CBE dry + propellant	MGA% * CBE dry = growth	CBE dry + propellant + growth	CBE dry + growth

2.6.1 Mass Growth

The COMPASS Team uses the AIAA S–120–2006, “Standard Mass Properties Control for Space Systems,” as the guideline for its mass growth calculations. Table 2.8 shows the percent mass growth of a piece of equipment according to a matrix that is specified down the left-hand column by level of design maturity and across the top by subsystem being assessed.

The COMPASS Team’s standard approach is to accommodate for a total growth of 30 percent or less on the dry mass of the entire system. The percent growth factors shown above are applied to each subsystem before an additional growth is carried at the system level, in order to ensure an overall growth of 30 percent. Note that for designs requiring propellant, growth in the propellant mass is either carried in the propellant calculation itself or in the ΔV used to calculate the propellant required to fly a mission.

A timeline shows how the various mass margins are reduced and consolidated over the mission’s life span. The system-integration engineer carries a system-level MGA, called “margin”, in order to reach a total system MGA of 30 percent. This is shown as the mass growth for the allowable mass on the authority to precede line in mission time. After setting the margin of 30 percent in the preliminary design, the rest of the steps shown below are outside the scope of the COMPASS Team.

TABLE 2.8.—MGA AND DEPLETION SCHEDULE (AIAA S-120-2006)

Major category	Maturity code	Design maturity (basis for mass determination)	MGA (%)												
			Electrical/electronic components			Structure	Brackets, clips, hardware	Battery	Solar array	Thermal control	Mechanisms	Propulsion	Wire harness	Instrumentation	ECLSS, crew systems
			0 to 5 kg	5 to 15 kg	>15 kg										
E	1	Estimated (1) An approximation based on rough sketches, parametric analysis, or undefined requirements; (2) A guess based on experience; (3) A value with unknown basis or pedigree	30	25	20	25	30	25	30	25	25	25	55	55	23
	2	Layout (1) A calculation or approximation based on conceptual designs (equivalent to layout drawings); (2) Major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	Prerelease designs (1) Calculations based on a new design after initial sizing but prior to final structural or thermal analysis; (2) Minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
	4	Released designs (1) Calculations based on a design after final signoff and release for procurement or production; (2) Very minor modification of existing hardware; (3) Catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	Existing hardware (1) Actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes; (2) Values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
	6	Actual mass Measured hardware	No mass growth allowance—Use appropriate measurement uncertainty values												
	7	Customer furnished equipment or specification value	Typically a “not-to-exceed” value is provided; however, contractor has the option to include MGA if justified												

2.6.2 Power Growth

The COMPASS Team uses a 30 percent growth on the bottoms-up power requirements of the vehicle subsystems when modeling the amount of required power. No additional margin is carried on top of this power growth. The Power System assumptions for this study will be show in Section 3.1.1.2 on the PEL.

2.7 Redundancy Assumptions

The titan submarine was designed to be single fault tolerant in the design of the subsystems, at least where possible.

3.0 Baseline Design

3.1 System Level Summary

This study focused on the conceptual design of the Titan Submarine. Though recognizing that the Titan entry system/cruise stage and LV are key parts of an overall mission conceptual design, funding and time did not permit delving deeply into the other two elements. That would be part of a Phase-2 NIAC study.

This section summarizes the Titan Submarine conceptual design, and touches on the LV and Titan entry system aspects of the missions that were assessed in this study phase.

3.1.1 Titan Submarine Concept Drawings and Descriptions

The major components that make up the Titan Submarine configuration include: the main hull, a sail containing the communication antenna, a mast for science and communications, two ballast tanks, the propulsion system, and a hydrodynamic skin. Figure 3.1 shows the Titan Submarine and these major components that make up the overall size and shape of the design.

The hull is the primary structure of the submarine. It is a pressurized cylinder that houses all of the internal subsystem components and provides mounting for the sail structure, ballast tanks, propulsion system, hydrodynamic skin, and many of the Science and GN&C components that need an unobstructed view or access to the outside of the hull. Mounted vertically off the top of the hull is the sail structure. The sail structure provides the required area for the patch antennas, mounted on both sides, as well as provides the mounting for the deployable mast, located on top of the sail structure. Contained on top of the half-meter tall mast are the science SI (required to be 1-m above the surface) and the meteorology sensor, while an omni antenna is mounted on each side of the mast. The mast is folded down along the side of the sail for stowage and is deployed once on the surface of Titan. Figure 3.2 shows the stowed configuration of the Titan Submarine. A ballast tank is mounted to each side of the hull and above the hull's centerline. The propulsion system consists of four thrusters, each mounted out at the end of a stabilizer that is mounted to the aft end of the hull structure. The use of four thrusters allows for pitch and yaw steering while submerged, as well as allowing the bottom pair of thrusters to be utilized to propel the submarine while at the surface. Finally, a hydrodynamic skin is wrapped around the hull encompassing

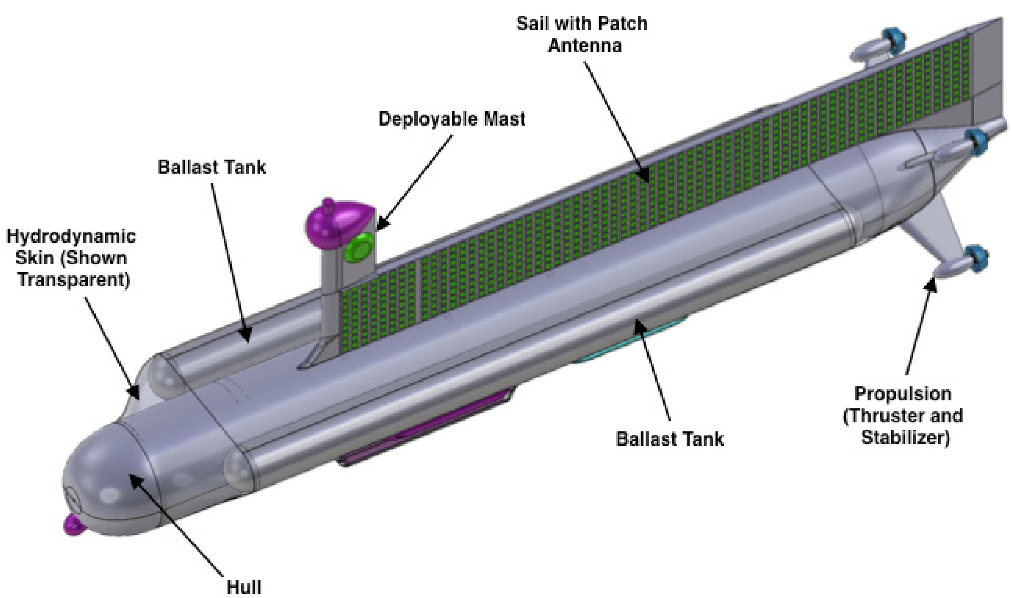


Figure 3.1.—Major components comprising the Titan Submarine.

the two ballast tanks and several of the external Science and GN&C components in order to reduce the drag created by these components as well as minimize the interference drag created between the ballast tanks and the hull structure. This skin also provides the interface for mounting the two Science SS Arrays and the two Sonar Transducers from the GN&C system. All of the components contained outside the hull structure can be seen in Figure 3.3. Not shown in the images is the foam that will be located in the gaps between the ballast tanks and hull underneath the hydrodynamic skin. This foam will help improve the buoyancy and stability of the submarine while submerged and at the surface.

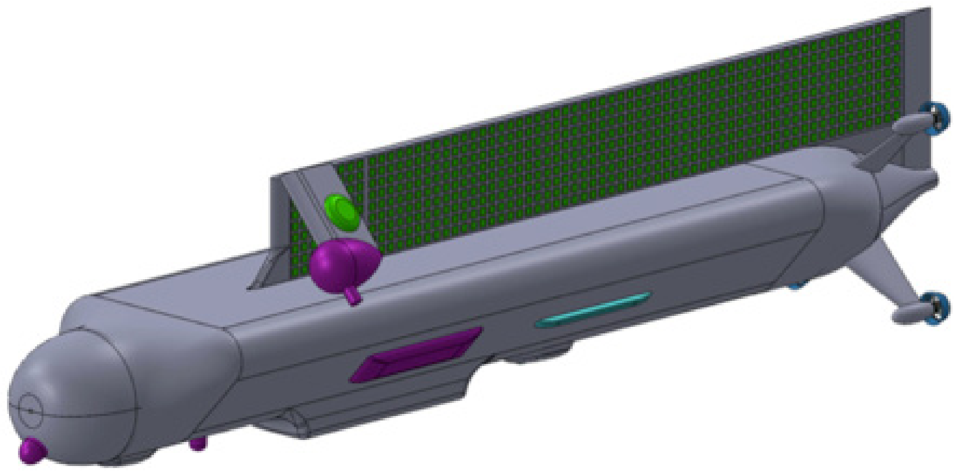


Figure 3.2.—Stowed configuration of the Titan Submarine.

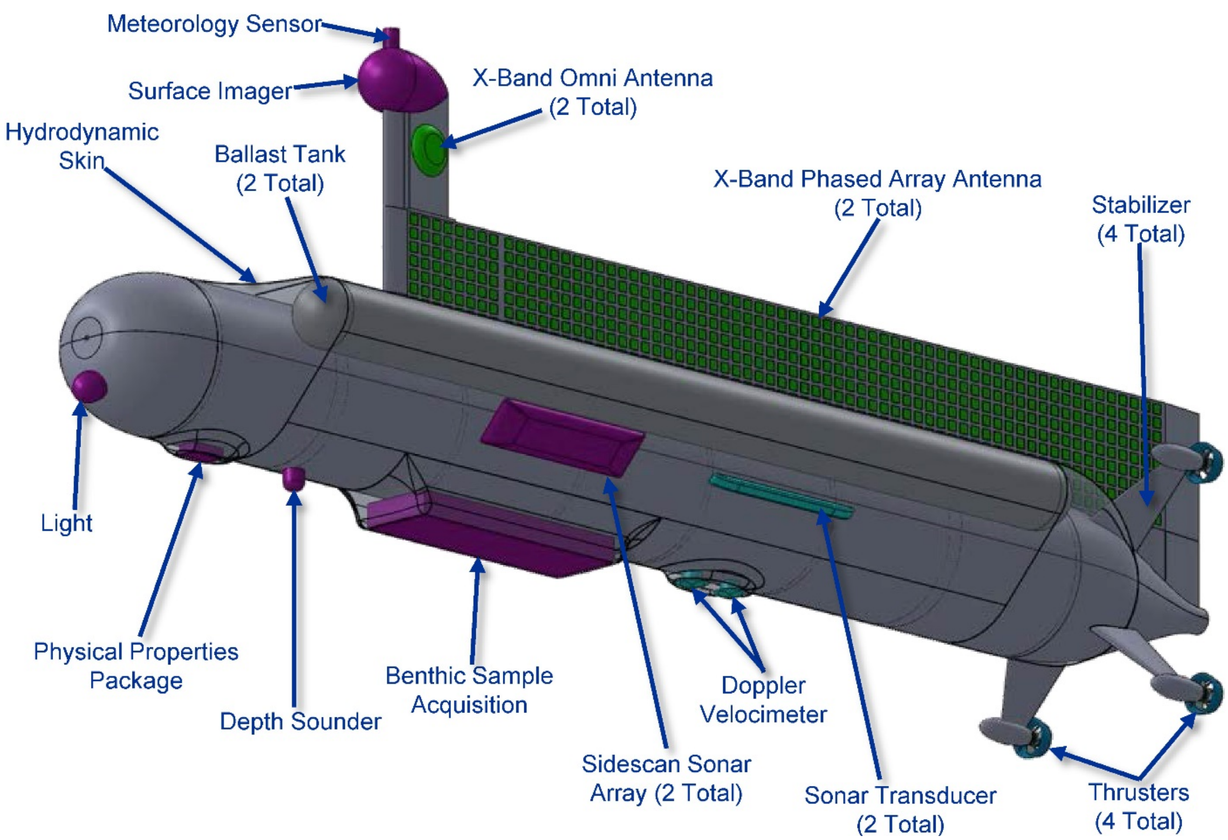


Figure 3.3.—External components on the Titan Submarine.

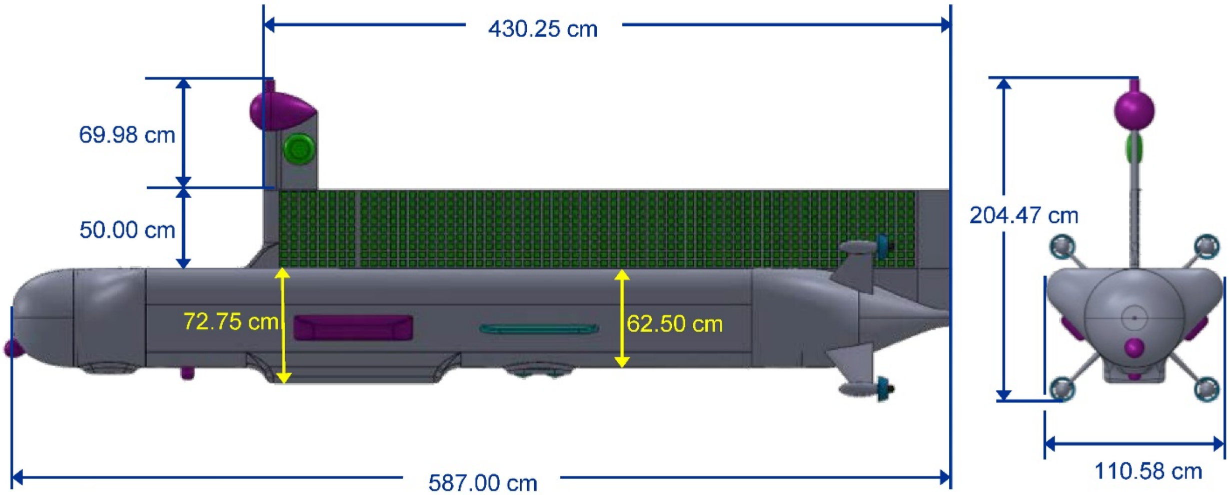


Figure 3.4.—Overall deployed dimensions of the Titan Submarine.

Overall dimensions of the Titan Submarine can be seen in Figure 3.4. The overall length of the submarine is driven by the 587 cm (19.3 ft) long hull structure, while the width is driven by the combination of the 62.5 cm (2 ft) diameter hull structure in combination with the two 27 cm. (0.9 ft) diameter ballast tanks. The height is driven by the need for the SI to be 1 m (3.3 ft) above the surface in combination with the hull diameter and the length of the lower two stabilizers and thrusters.

All of the components contained inside the pressurized hull structure can be seen in Figure 3.5. The inside of the hull skin and its six ring supports are covered with a 3 cm (1.1 in.) thick layer of foam insulation in order to maintain the proper temperatures inside the hull and minimize the heat that escapes the hull. Two additional larger structural rings, one near the front and another near the rear, cut through the insulation, thus inducing a heat sink between the inside and outside of the hull. This heat sink was accounted for in determining the thickness of the insulation to meet the thermal requirements. It is these two large rings that provide the support for the internal structural "cage" that provides the interfaces to all of the other internal components, as well as provides the interface to hold the submarine inside of the lifting body from launch through the descent phase at Titan. Further details on the insulation can be found in the TCS Section 4.7, while additional detail on the structures can be found in the Section 4.8, Structures and Mechanisms.

The structural "cage" located within the hull provides the mounting interface for all of the subsystem components contained within the pressurized hull structure. It is desired to locate the science electronics as far away from the SRGs as possible to avoid any interference that may be generated by the SRGs. For this reason, all of the science electronics were located at the front of the hull and mounted directly to the inside of the "cage" structure, with the exception of the UI Sensor Box that is mounted to a panel on the front of the cage. This location allows the imager to look out a 4 in^2 window located at the front of the hull while being contained inside the insulated pressurized environment. The IMUs and electronics for the GN&C system are located directly behind the science inside the cage along with the flight controller of the C&DH system. Finally, just behind the C&DH and GN&C components is the Power Management and Distribution (PMAD) electronics followed by the two SRGs. Not shown in Figure 3.5 is the 180 kg (397 lbm) of permanent lead ballast that would be located between the bottom side of the "cage" structure and the insulation. This will help to lower the center of gravity (CG) of the submarine, thus helping with buoyancy and stability issues. Further analysis needs to be done to better locate the internal components

in order to drive the CG to a location that maximizes the stability and buoyancy of the submarine. An additional view of the internal components can be seen in Figure 3.6, while Figure 3.7 and Figure 3.8 show transparent views of the Titan Submarine.

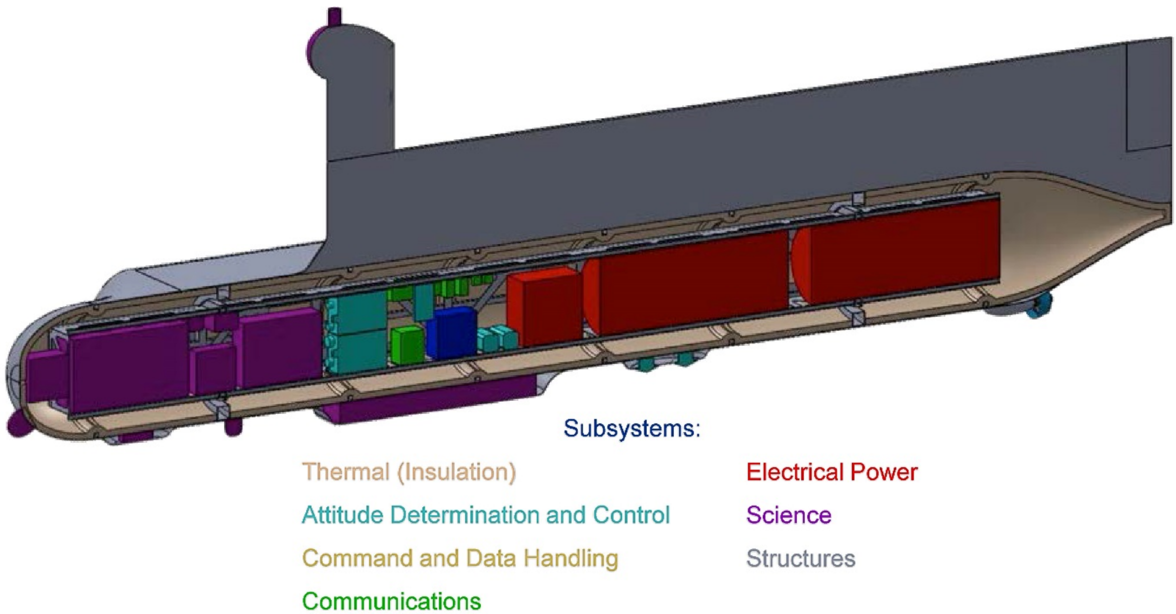


Figure 3.5.—Cross-sectional view of the Titan Submarine.

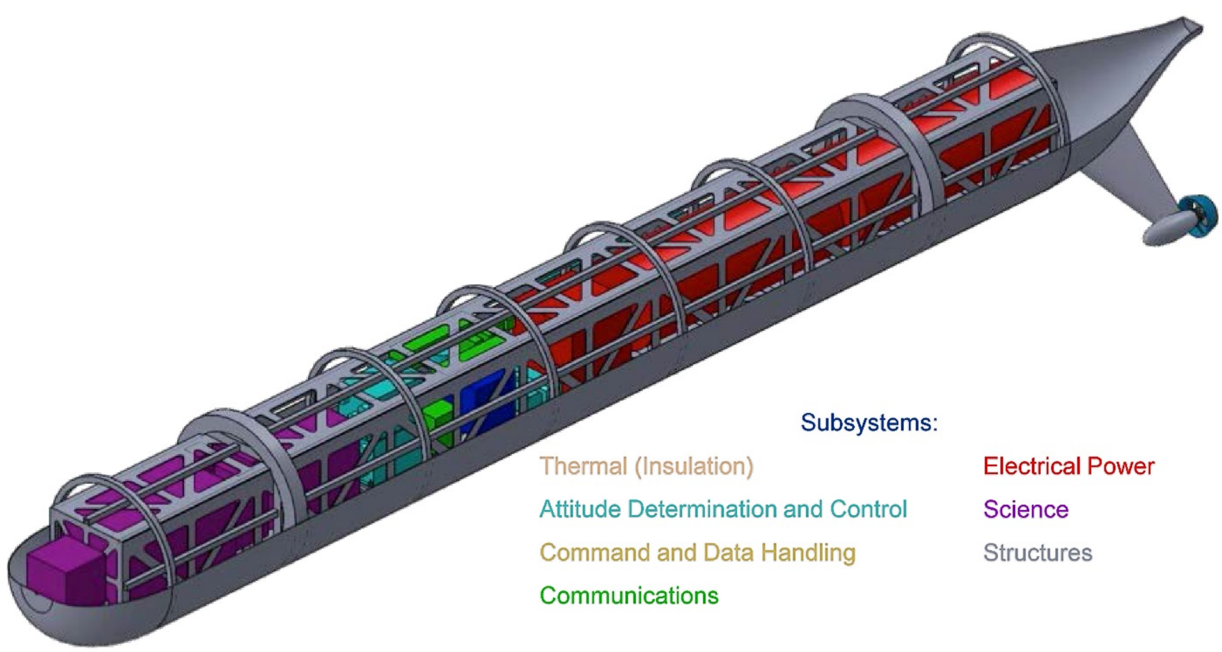


Figure 3.6.—Internal layout of the Titan Submarine.

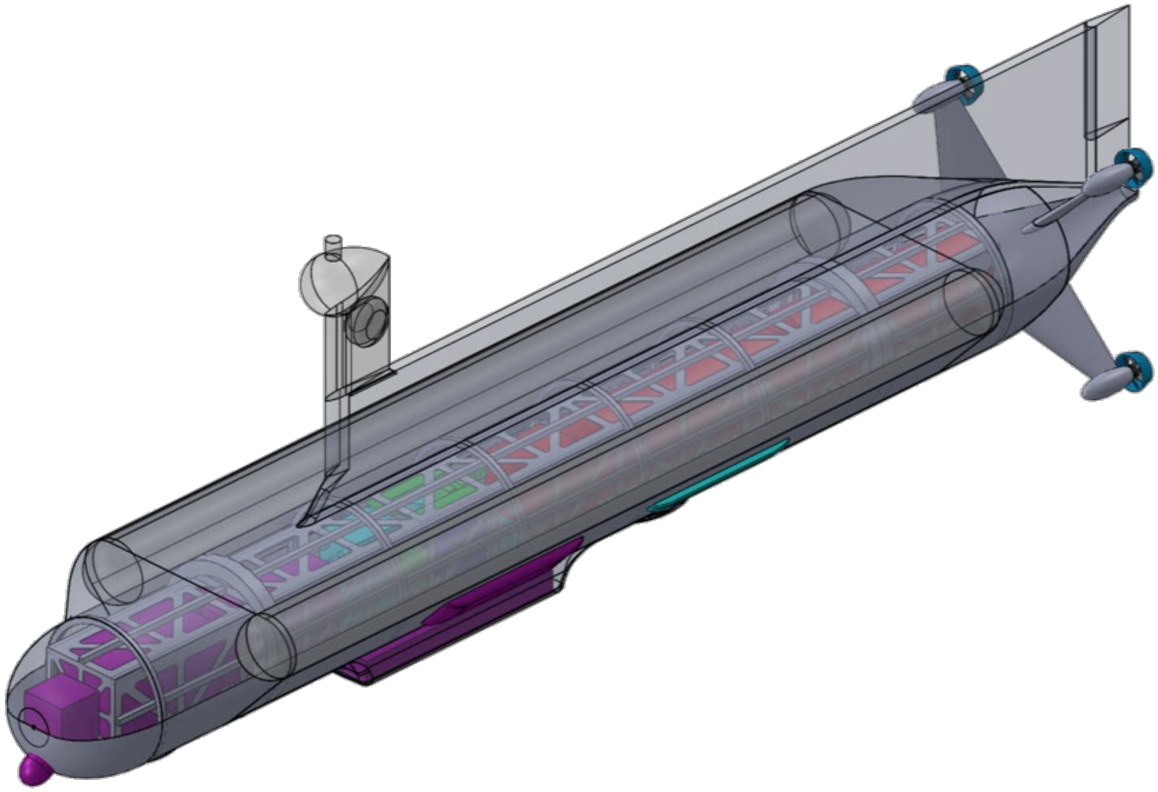


Figure 3.7.—Transparent view of the Titan Submarine.

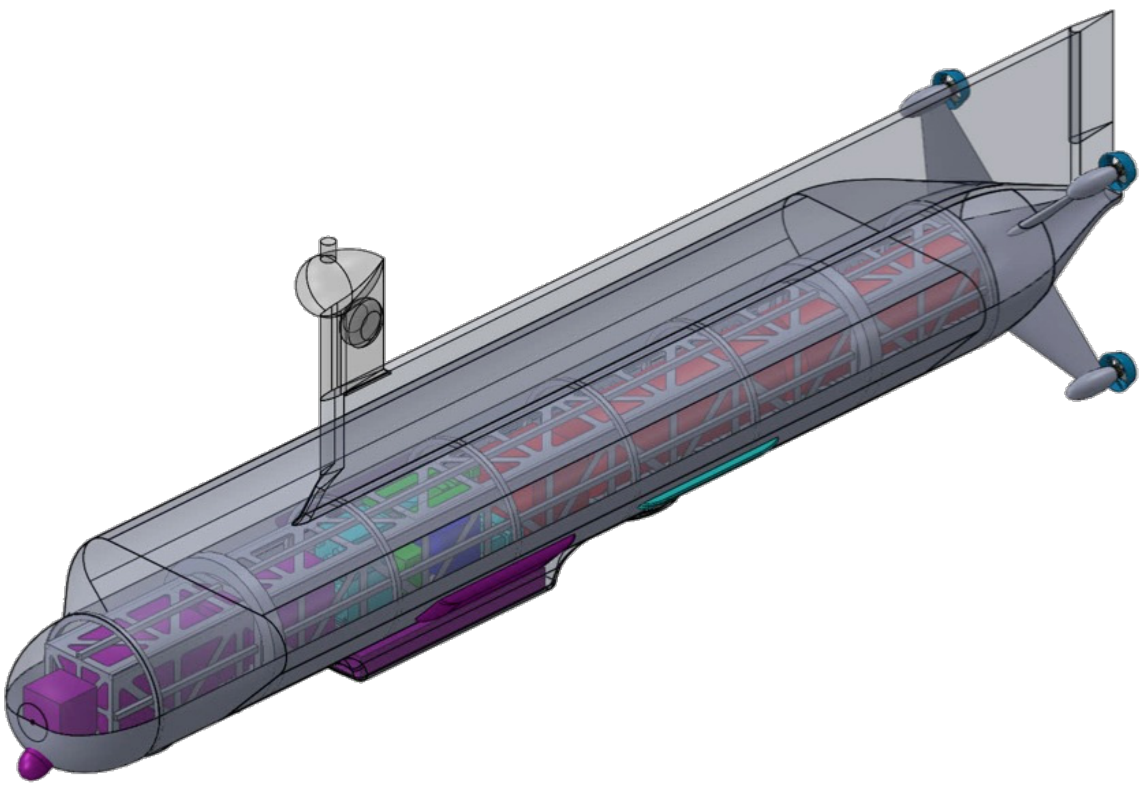


Figure 3.8.—Transparent view of the Titan Submarine (ballast tanks removed).

3.1.1.1 Master Equipment List (MEL)

The Titan Submarine MEL is shown in Table 3.1. The MEL presents a summary mass listing for all subsystems of the Titan sub along with their mass growth allowances based on the maturity of the subsystem components.

1.1.1.1 Titan Submarine Architecture Summary

The MEL shown in Table 3.2 captures the bottoms-up estimation of CBE and growth percentage of the Titan Submarine that the subsystem designers calculated for each line subsystem. In order to meet the total required system mass growth of 30 percent, an allocation is necessary for growth on basic dry mass at the system level, in addition to the growth calculated on each individual subsystem. This additional system-level mass is counted as part of the inert mass to be flown. The additional system-level growth mass also impacts the total ballasting required on the sub to assure buoyancy control.

3.1.1.2 Power Equipment List (PEL)

To model the power systems in this Titan Submarine design study, ten modes of operation were defined for the study. These modes were defined based on the mission profile and they identify which items and subsystems of the sub are operating, and which items are dormant and require no power, at any time throughout the mission. The definitions of these modes are shown in Table 3.3.

Table 3.4 and Table 3.5 show the assumptions about the power requirements across all modes of operation. The power requirements from the bottoms-up analysis on the titan sub shown in those tables are used by the power system designers to size the power system components and by the Thermal Control System (TCS) lead to manage the waste heat from these components.

TABLE 3.1.—MEL FOR THE TITAN SUBMARINE

Description Case 1—Titan Sub CD-2014-114	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Titan Sub S/C	901.8	20.3	183.1	1085.0
Titan Sub	901.8	20.3	183.1	1085.0
Science Payload	91.0	30.0	27.3	118.3
Attitude Determination and Control (AD&C)	32.9	18.0	5.9	38.8
C&DH	44.0	30.0	13.2	57.2
Communications and Tracking	26.3	16.0	4.2	30.5
Electrical Power Subsystem	146.0	20.0	29.2	175.2
Thermal Control (Non-Propellant)	95.3	18.0	17.2	112.5
Propulsion	20.6	28.8	5.9	26.5
Propellant	0.0	0	0.0	0.0
Structures and Mechanisms	445.7	18.0	80.2	525.9

TABLE 3.2.—TITAN SUBMARINE ARCHITECTURE SUMMARY

S/C MEL Rack-up (Mass)—Case 1 Titan Sub CD-2014-114					
WBS	Main subsystems	Basic mass, kg	Growth, kg	Predicted mass, kg	Aggregate growth, %
06	Titan Sub S/C	901.8	183.1	1085.0	---
06.1	Titan Sub	901.8	183.1	1085.0	20
06.1.1	Science Payload	91.0	27.3	118.3	30
06.1.2	AD&C	32.9	5.9	38.8	18
06.1.3	C&DH	44.0	13.2	57.2	30
06.1.4	Communications and Tracking	26.3	4.2	30.5	16
06.1.5	Electrical Power Subsystem	146.0	29.2	175.2	20
06.1.6	Thermal Control (Non-Propellant)	95.3	17.2	112.5	18
06.1.7	Propulsion	20.6	5.9	26.5	29
06.1.8	Propellant	0.0	------	0.0	TBD
06.1.9	Not Used	0.0	0.0	0.0	TBD
06.1.10	Not Used	0.0		0.0	TBD
06.1.11	Structures and Mechanisms	445.7	80.2	525.9	18
	Element 1 consumables (if used)	0.0	------	0.0	---
	Estimated S/C dry mass (no prop, consumables)	901.8	183.1	1085.0	20
	Estimated S/C wet mass	901.8	183.1	1085.0	---
System level growth calculations titan sub					Total growth
	Dry mass desired system level growth	901.8	270.5	1172.4	30
	Additional Growth (carried at system level)	-------	87.4	--------	10
	Total wet mass with growth	901.8	270.5	1172.4	
Hydrostatic balance					
	Foam in voids between pressure hull and ballast	34.0			
	Additional lead ballast	180.0			
	Total wet mass with growth and balance			1386.4	

TABLE 3.3.—POWER MODES FOR THE TITAN SUBMARINE STUDY

Power Mode Names	Description	Duration
Launch	Ascent through Earth departure	60 min
Interplanetary Cruise	Keep-alive power during hibernation; occasional wake up and c/o	7 yr
Titan EDL	Entry, descent and splashdown	2 hr
Sub Activation and Checkout	Commissioning	1 wk
Dive/Surface		100 mi
Submerged Cruise	Including science and h/k comm. (low data rate)	8 hr
Surface Cruise	Including science and comm. (high data rate)	16 hr
Stationary Submerged Operations	Including science and h/k comm (low data rate)	8 hr
Stationary Surface Operations	Including science and comm. (high data rate)	16 hr
End of mission (EOM) Disposal		

TABLE 3.4.—PEL FOR THE TITAN SUBMARINE (MODES 1 TO 5)

WBS number	Description Case 1Titan Sub CD-2014-114	Power mode 1, W	Power mode 2, W	Power mode 3, W	Power mode 4, W	Power mode 5, W
	Power mode name	Launch	Interplanetary Cruise	Titan EDL	Sub Activation and Checkout	Dive/Surface
	Power mode duration	60 min	7 yr	2 hr	1 wk	100 min
06	Titan Sub S/C	60.0	70.0	90.0	648.0	635.0
06.1	Titan Sub	60.0	70.0	90.0	648.0	635.0
06.1.1	Science Payload	0.0	0.0	0.0	55.0	53.0
06.1.2	AD&C	0.0	0.0	0.0	63.0	52.0
06.1.3	C&DH	60.0	60.0	60.0	60.0	60.0
06.1.4	Communications and Tracking	0.0	10.0	30.0	30.0	30.0
06.1.5	Electrical Power Subsystem	0.0	0.0	0.0	0.0	0.0
06.1.6	Thermal Control (Non-Propellant)	0.0	0.0	0.0	0.0	0.0
06.1.7	Propulsion	0.0	0.0	0.0	440.0	440.0
06.1.8	Propellant	0.0	0.0	0.0	0.0	0.0
06.1.9	Not Used	0.0	0.0	0.0	0.0	0.0
06.1.10	Not Used	0.0	0.0	0.0	0.0	0.0
06.1.11	Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0
06.2	Entry System	0.0	0.0	0.0	0.0	0.0
06.3	Cruise Stage	0.0	0.0	0.0	0.0	0.0
	Bus Power, System Total	60.0	70.0	90.0	648.0	635.0
	30% growth	18.0	21.0	27.0	194.4	190.5
	Total Bus Power Requirement	78.0	91.0	117.0	842.4	825.5

TABLE 3.5.—PEL FOR THE TITAN SUBMARINE (MODES 6 TO 10)

WBS number	Description Case 1 Titan Sub CD-2014-114	Power mode 6, W	Power mode 7, W	Power mode 8, W	Power mode 9, W	Power mode 10, W
	Power mode name	Submerged Cruise	Surface Cruise	Stationary Submerged Operations	Stationary Surface Operations	EOM Disposal
	Power mode duration	8 hr	16 hr	8 hr	16 hr	0.0
06	Titan Sub S/C	645.0	573.5	207.0	411.0	128.0
06.1	Titan Sub	645.0	573.5	207.0	411.0	128.0
06.1.1	Science Payload	53.0	43.0	55.0	23.0	0.0
06.1.2	AD&C	62.0	53.0	62.0	53.0	53.0
06.1.3	C&DH	60.0	60.0	60.0	60.0	60.0
06.1.4	Communications and Tracking	30.0	280.0	30.0	275.0	15.0
06.1.5	Electrical Power Subsystem	0.0	0.0	0.0	0.0	0.0
06.1.6	Thermal Control (Non-Propellant)	0.0	37.5	0.0	0.0	0.0
06.1.7	Propulsion	440.0	100.0	0.0	0.0	0.0
06.1.8	Propellant	0.0	0.0	0.0	0.0	0.0
06.1.9	Not Used	0.0	0.0	0.0	0.0	0.0
06.1.10	Not Used	0.0	0.0	0.0	0.0	0.0
06.1.11	Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0
06.2	Entry System	0.0	0.0	0.0	0.0	0.0
06.3	Cruise Stage	0.0	0.0	0.0	0.0	0.0
	Bus Power, System Total	645.0	573.5	207.0	411.0	128.0
	30% growth	193.5	172.0	62.1	123.3	38.4
	Total Bus Power Requirement	838.5	745.5	269.1	534.3	166.4

3.1.2 Launch Vehicle (LV)

Since this concept study focused mainly on the details of the Titan submarine, this section covers those LV aspects that were necessary for the design of the submarine. The detailed LV selection and definition of interfaces would be part of a Phase II study.

Sending a substantial payload (the Titan submarine and the Titan entry system/cruise stage) to the Saturn system will require a LV with substantial lift capability. Surveying the stable of LVs available under the NASA Launch Services contract, the Atlas V 551 was chosen as the representative launcher for the Titan submarine conceptual design study. It permits a substantial payload mass capability to high energy trajectories, as shown in Table 3.6.

LV performance was obtained from the NASA Launch Services web site at: http://elvperf.ksc.nasa.gov/pages/default.aspx

The Atlas V 551 features a 5 m (16.4 ft) diameter payload fairing, five strap-on solid propellant boosters and a Centaur upper stage with a single main engine. Given a thumbnail estimate of 3,000 kg (6,615 lbm) for the Titan submarine and the Titan entry system/cruise stage, this launcher can still achieve a high energy trajectory to the Saturn system. Though it would still require planetary flybys and gravity assist maneuvers to reach Titan, the Atlas V 551 configuration is the most capable vehicle in the NLS stable.

Detailed information on the payload fairing envelope and environmental requirements required for the submarine conceptual design were obtained from the latest version of the Atlas V Launch Services User's Guide at: http://www.ulalaunch.com/Products_AtlasV.aspx

Figure 3.9 presents rough estimates of payload mass to Saturn achievable with a variety of heavy lift LVs. To achieve the requisite payload mass to Saturn, a Venus-Venus-Jupiter (VVJ) flyby sequence would be required to increase transfer orbit energy beyond the capability of the Atlas V 551, Delta IV Heavy or Falcon Heavy LVs. To send the Titan Submarine and its lifting body directly to the Saturn System would require the use of the Space Launch System (SLS).

TABLE 3.6.—NLS LV CAPABILITIES FOR THE TITAN SUBMARINE MISSION

		Separated S/C mass, kg													
	Vehicle	Antares 122	Antares 132	Athena II	Falcon 9 v1.1	Atlas V 401	Atlas V 411	Atlas V 421	Atlas V 431	Atlas V 501	Atlas V 511	Atlas V 521	Atlas V 531	Atlas V 541	Atlas V 551
	Launch Site	WFF	WFF	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS	CCAFS
C_3 (km^2/s^2)	–10	1,160	1,515	485	4,845	3,710	4,760	5,590	6,285	2,690	3,995	5,055	5,920	6,680	7,275
	–5	990	1,320	425	4,210	3,360	4,335	5,110	5,745	2,385	3,620	4,615	5,415	6,125	6,675
	–3.6	------	1,300	-----	------	------	------	------	------	-------	------	------	------	------	------
	0	845	------	370	3,635	3,035	3,930	4,655	5,235	2,095	3,265	4,195	4,940	5,595	6,105
	5	715	------	315	3,105	2,720	3,550	4,225	4,755	1,825	2,930	3,795	4,490	5,095	5,570
	10	600	------	265	2,625	2,425	3,185	3,815	4,300	1,570	2,610	3,415	4,065	4,625	5,060
	15	495	------	225	2,175	2,145	2,845	3,435	3,870	1,335	2,310	3,060	3,660	4,180	4,585
	20	------	------	185	1,765	1,880	2,525	3,070	3,465	1,115	2,030	2,730	3,285	3,765	4,140
	25	------	------	150	1,390	1,630	2,230	2,735	3,090	910	1,765	2,420	2,935	3,380	3,730
	30	------	------	120	1,040	1,400	1,950	2,425	2,745	725	1,515	2,130	2,610	3,020	3,345
	35	------	------	95	715	1,185	1,695	2,135	2,425	560	1,290	1,860	2,315	2,690	2,995
	40	------	------	70	415	985	1,455	1,870	2,130	405	1,080	1,615	2,040	2,390	2,670
	45	------	------	50	-----	800	1,240	1,625	1,860	270	885	1,390	1,790	2,120	2,380
	50	------	------	30	-----	635	1,045	1,410	1,625	155	715	1,190	1,565	1,875	2,120
	60	------	------	-----	-----	350	720	1,045	1,225	-------	420	855	1,195	1,475	1,695

WFF = Wallops Flight Facility
CCAFS = Cape Canaveral Air Force Station

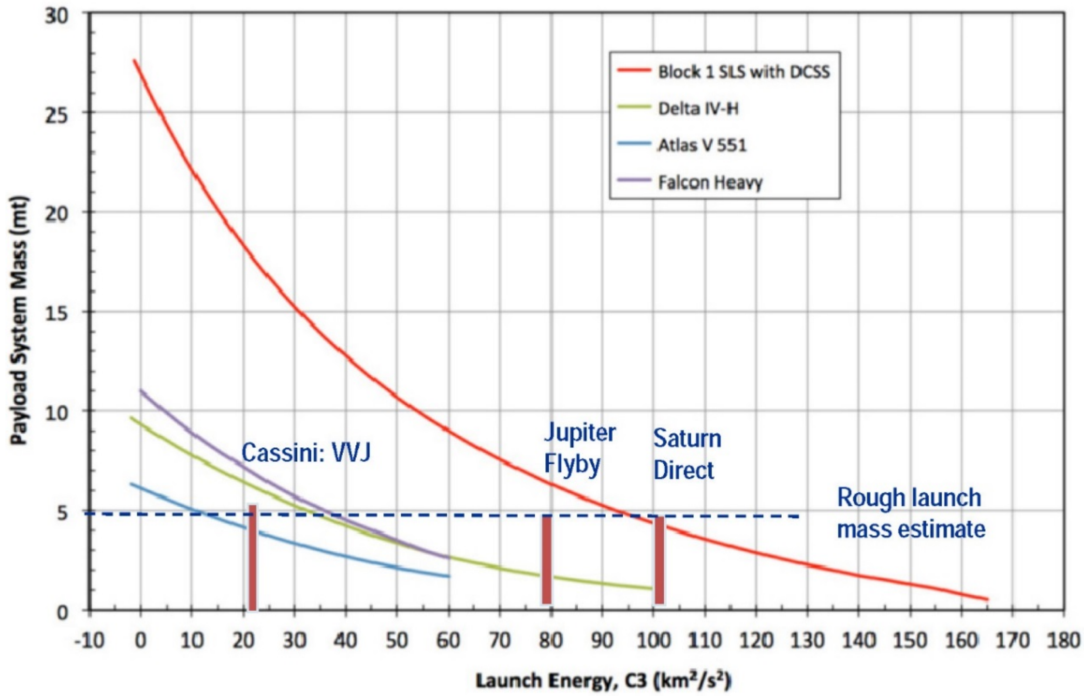


Figure 3.9.—Comparison of LV performance.

3.1.3 Titan Entry System/Cruise Stage

The Titan submarine will require a system to perform atmospheric entry, descent and landing (EDL) operations at the Saturnian moon, and to serve as a support stage during the interplanetary cruise phase of the mission. The system must provide:

- Interfaces with the LV
- Propulsive capability to perform course corrections during interplanetary flight
- Communications with Earth
- Navigation information from Earth
- Capability to reject heat from the SRGs during interplanetary flight
- Ability to perform atmospheric EDL on Kraken Mare

An aerovehicle entry system/cruise stage was chosen as the notional system to perform the functions listed above. Titan has a dense atmosphere, and an aerovehicle entry system can not only provide protection from the heat levels generated during entry, but substantial cross-range capability in atmospheric flight to assure a successful targeting of, and landing on Kraken Mare. A system similar in size, shape and descent capabilities to the Boeing X-37B was chosen for the purposes of this study since the X-37B has already demonstrated autonomous de-orbit, entry and targeted landings on Earth after long duration space flight in LEO.

In a Phase II study, this system will be investigated further to determine the requirements on the aerovehicle’s thermal protection system to survive direct entry into Titan’s dense atmosphere, requirements on wing and control surfaces for atmospheric flight at Titan, and its ability to execute a landing on the surface of Kraken Mare.

Views of the aerovehicle components and how the Titan submarine might fit inside such an aerovehicle are shown in Figure 3.10.

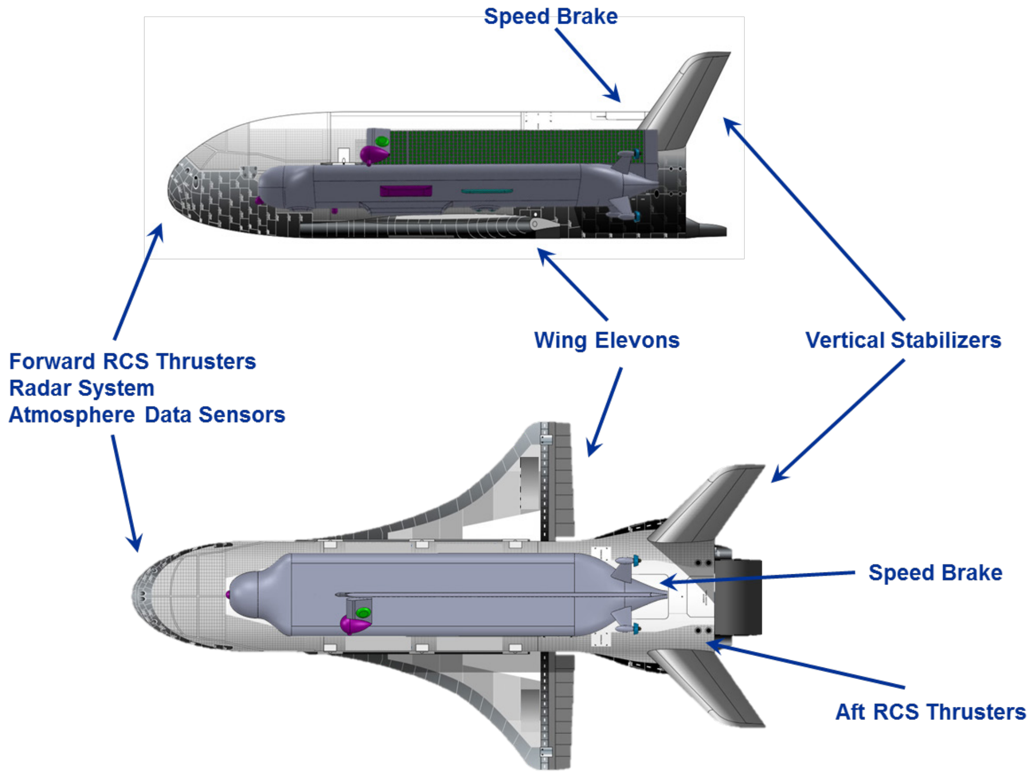


Figure 3.10.—Titan Submarine inside aerovehicle. Acknowledgements: X-37B outline courtesy of Giuseppe De Chiara (used with permission) and http://en.wikipedia.org/wiki/Boeing_X-37#mediaviewer/File:X_37B_OTV-2_01.jpg.

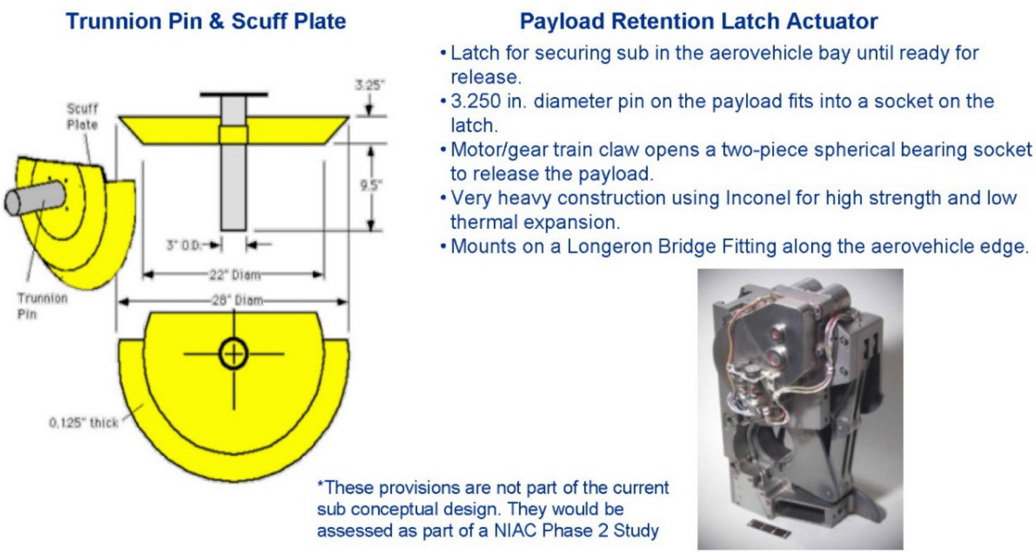


Figure 3.11.—Notional structural/mechanical interface accommodations between the aerovehicle and the Titan Submarine.

The aerovehicle would provide the structural/mechanical interfaces to the Titan submarine during launch, cruise and through EDL on Titan. The aerovehicle systems would be commanded by the submarine's flight computer via umbilical connections. After Titan landing, those structural and electrical interfaces would have to be severed, and the aerovehicle separated from the submarine. Notionally, the submarine could be mounted into the aerovehicle through the use of trunnion pins and a keel fitting with

retention latch actuators, similar to the way that large payloads were mounted in the cargo bay of the Space Shuttle Orbiters (Figure 3.11). Since the aerovehicle would separate from the submarine, not vice versa, the trunnion pins and keel fittings would be on the aerovehicle, and the retention latch actuators would be on the submarine. Alignment guides on the latch actuators would help assure a clean separation of the aerovehicle from the submarine after landing on Kraken Mare.

Separation of the submarine after landing is discussed further in Section 3.2, Concept of Operations. Detailed development of the systems required would be part of a Phase II study.

3.2 Concept of Operations

The concept of operations (CONOPS) for the TSSM mission is divided into the following mission phases:

- Launch Site Operations
- Launch and Ascent
- Park Orbit and Trans-Titan insertion (TTI)
- Interplanetary Cruise
- Titan Entry, Descent and Splashdown (EDS)
- Sub Activation and Checkout
- Mare Sorties including:
    - Dive/Surface Operations
    - Submerged Cruise
    - Surface Cruise
    - Stationary Submerged Operations
    - Stationary Surface Operations
- End of Mission

Each mission phase is presented in detail in the following paragraphs.

3.2.1 Launch Site Operations

The S/C will be launched on an Atlas V 551 Expendable Launch Vehicle (ELV) from Complex 40 at CCAFS, Florida. Processing of the LV and the S/C will occur at CCAFS facilities and facilities at the NASA Kennedy Space Center (KSC) industrial area.

The S/C (aerovehicle and Titan Submarine) will arrive at the Payload Processing Facility (PPF). Following receiving operations, the customer is responsible to perform final assembly and buildup of the payload to its launch configuration. Assembly operations in a PPF do not include hazardous operations involving ordnance, cryogenics, or hypergolic propellants. Customer payload functional testing is conducted by customers using their own payload-unique ground checkout equipment. When testing is complete and the payload is ready to move to the next checkout area, the ground checkout equipment usually remains in the PPF (which is dedicated to that particular payload until the payload is launched).

Movement to the Hazardous Processing Facility (HPF) is the responsibility of the customer, movement to the launch pad is the responsibility of the ELV contractor. KSC provides forklift and crane operators as required and scheduled. Transportation containers and special carriers must be provided by the customer. Any special environmental conditioning required must also be provided or procured by the customer.

The S/C will arrive at one of several possible HPFs. The S/C is removed from its transporter or container and installed in a test or assembly stand provided by the customer. Activities which may be

conducted in the HPF's include propellant loading (hydrazine, monomethyl hydrazine (MMH), and dinitrogen tetraoxide (N_2O_4)) as well as installation of solid propellant apogee motors, ordnance separation devices, and other potentially explosive or hazardous items. Operations in an HPF are conducted by the customer with assistance by KSC/CCAFS as specified in the Launch Site Support Plan (LSSP).

Since the Titan submarine would include nuclear material, the HPF would be one of three facilities for Processing Nuclear Missions: NASA Payload Hazardous Servicing Facility (PHSF), the Multi-Operation Support Building (MOSB) or the Radioisotope Thermoelectric Generator Facility (RTG-F). PHSF is the only NASA facility certified to accept and process multi-hazardous payloads with nuclear components. MOSB provides office space, meeting rooms, etc. and is a companion building to the PHSF with communication, phone and data links wired directly to PHSF. RTG-F is located in the KSC Industrial Area. It is a secure site/building dedicated for nuclear power source processing and storage.

3.2.1.1 Nuclear Materials

For any U.S. space mission involving the use of Radioisotope Power Systems (RPSs), radioisotope heater units, nuclear reactors, or a major nuclear source, launch approval must be obtained from the Office of the President per Presidential Directive/National Security Council Memorandum No. 25 (PD/NSC-25), “Scientific or Technological Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space,” paragraph 9, as amended May 8, 1996. The approval decision includes an independent evaluation by an ad hoc Interagency Nuclear Safety Review Panel (INSRP) comprised of representatives from NASA, the Department of Energy (DOE), the Department of Defense, and the Environmental Protection Agency, with an additional technical advisor from the Nuclear Regulatory Commission.

The process begins with development of a LV databook (i.e., a compendium of information describing the mission, launch system, and potential accident scenarios including their environments and probabilities). DOE uses the databook to prepare a Preliminary Safety Analysis Report for the space mission. Three Safety Analysis Reports (SARs) are typically produced and submitted to the mission’s INSRP—the PSAR, an updated SAR (draft final SAR), and a final SAR. The DOE project office responsible for providing the nuclear power system develops these documents.

The ad hoc INSRP conducts its nuclear safety/risk evaluation and documents their results in a nuclear Safety Evaluation Report (SER). The SER contains an independent evaluation of the mission radiological risk. DOE uses the SER as its basis for accepting the SAR. If the DOE Secretary formally accepts the SAR-SER package, it is forwarded to the NASA Administrator for use in the launch approval process.

NASA distributes the SAR and SER to the other cognizant Government agencies involved in the INSRP, and solicits their assessment of the documents. After receiving responses from these agencies, NASA conducts internal management reviews to address the SAR and SER and any other nuclear safety information pertinent to the launch. If the NASA Administrator recommends proceeding with the launch, then a request for nuclear safety launch approval is sent to the director of the Office of Science and Technology Policy within the Office of the President.

All space flight equipment that contain or use radioactive materials must be identified and analyzed for radiological risk. Site-specific ground operations and radiological contingency plans must be developed commensurate with the risk represented by the planned launch of nuclear materials. Contingency planning, as required by the National Response Plan, includes provisions for emergency response and support for source recovery efforts. NASA Procedural Requirements (NPR) 8710.1, Emergency Preparedness Program and NPR 8715.2, NASA Emergency Preparedness Plan Procedural Requirements—Revalidated address the NASA emergency preparedness policy and program requirements.

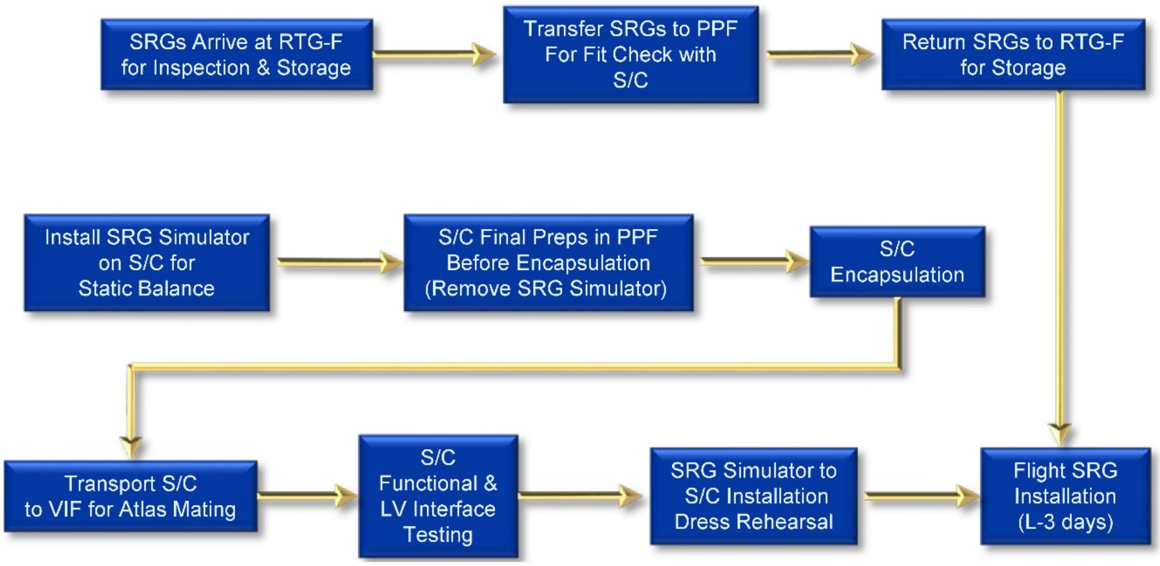


Figure 3.12.—Processing the SRGs for the Titan Submarine.

3.2.1.2 SRG Processing

The SRGs for the Titan submarine will follow a processing route through the RTG-F. A summary of the notional SRG flow and how it intersects with S/C and LV processing is illustrated in Figure 3.12.

3.2.1.3 LV Processing

The Atlas V 551 LV processing flow occurs independently of the S/C processing until the S/C is encapsulated in an HPF. This process involves mating with the S/C to LV adapter and enclosing the S/C in the LV's payload fairing. This is shown in Figure 3.13. Once encapsulated in the payload fairing, the LV team will transport the S/C and fairing to the Vertical Integration Facility (VIF) at the launch complex.

Upon arrival at the pad, the ELV contractor has responsibility for installing the payload onto the LV. The KSC Launch Site Support Manager (LSSM) coordinates interfaces between the LV contractor and the customer.

Spacecraft to LV integrated testing will occur after mating to the Centaur upper stage. Then, the SRG installation into the titan submarine will be rehearsed with a simulator. After a successful rehearsal, the flight unit will be installed and the S/C closed out for launch. These events are illustrated in Figure 3.14 and Figure 3.15, respectively. After SRG installation, and the sub is buttoned-up for launch, the hull will be pressurized to 1.03 MPa (150 psi) so that it can withstand the pressure it would experience at its maximum depth capability under the surface of Kraken Mare.

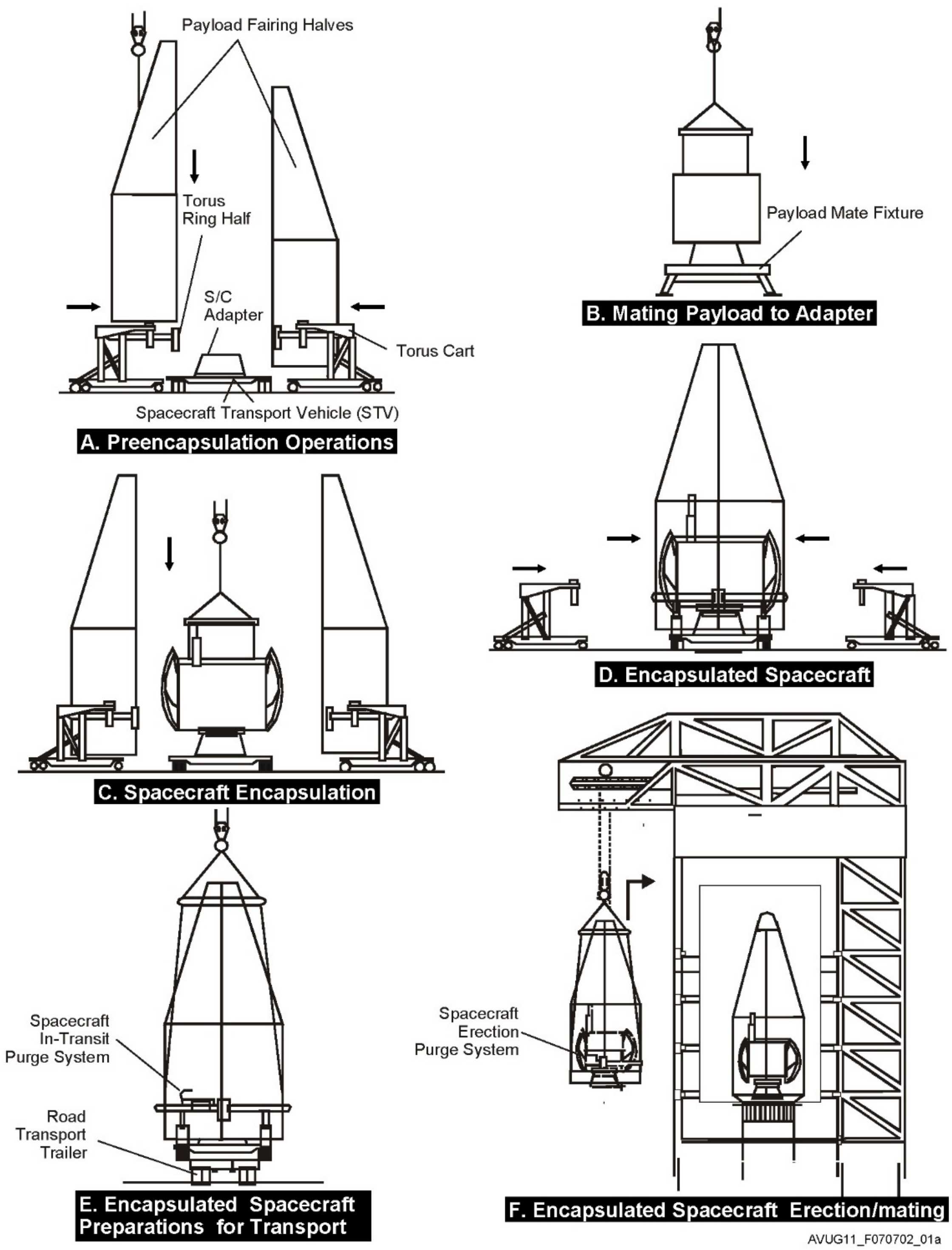


Figure 3.13.—S/C encapsulation.

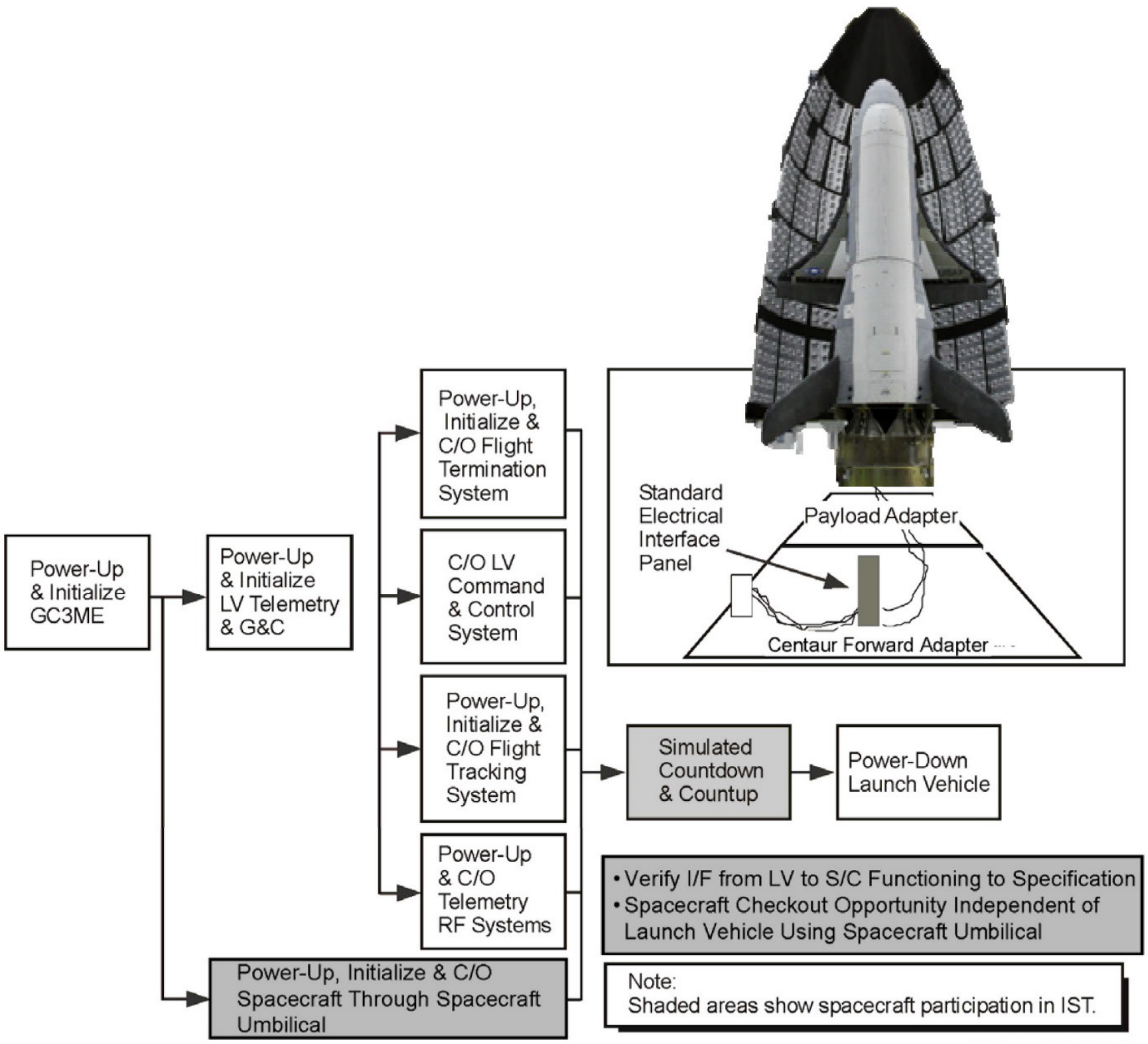


Figure 3.14.—S/C/LV integrated testing.

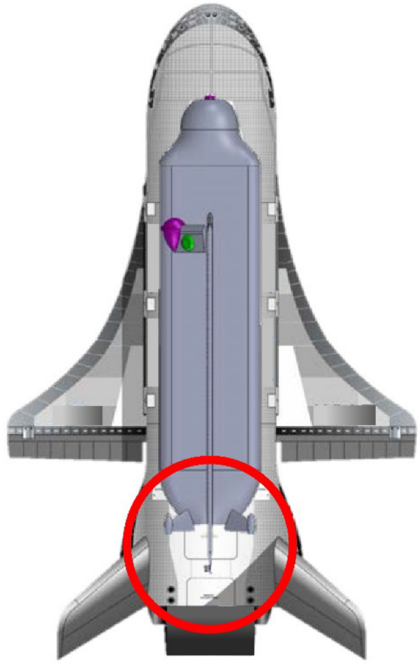


Figure 3.15.—SRG installation in the VIF. Acknowledgements: X-37B outline courtesy of Giuseppe De Chiara (used with permission) and http://en.wikipedia.org/wiki/Boeing_X-37#mediaviewer/File:X_37B_OTV-2_01.jpg. Titan Submarine CAD model created by T. Packard, NASA Glenn COMPASS Team.

3.2.2 LV Ascent, Park Orbit and TTI

During the final launch countdown, the S/C systems undergo a pre-launch checkout. A successful pre-launch checkout results in S/C "GO" for launch and the S/C is transitioned from ground to internal power approximately 5 min before launch. Critical heaters are enabled and the S/C's C&DH system is powered to provide heater control. The Atlas V 551 launch sequence is shown in Figure 3.16.

Centaur Main Engine Cutoff-1 (MECO-1) leaves the vehicle in LEO park orbit. During park orbit coast, the Centaur orients the stack to a thermal control attitude and initiates a BBQ roll to maintain thermal equilibrium. BBQ roll ends as Centaur aligns to burn attitude for TTI.

After the TTI burn, the Centaur commands activation of the S/C's avionics and IMU's are calibrated. Centaur maneuvers the vehicle to an attitude which optimizes Earth communications. Typically, 169 sec after the Centaur's final burn, the S/C is separated. The Centaur separation signal activates the S/C attitude control system and reaction control system. Communications begins transmitting telemetry at separation via X-band omni. After another 370 sec, Centaur performs a collision and contamination avoidance maneuver to avoid recontact with the vehicle.

The S/C thrusters are used to null separation disturbances and to re-acquire the separation attitude. Ranging is done to determine orbit parameters and create a state vector. The state vector will be used to determine the attitude and magnitude required for the first course correction burn to be performed by the S/C.

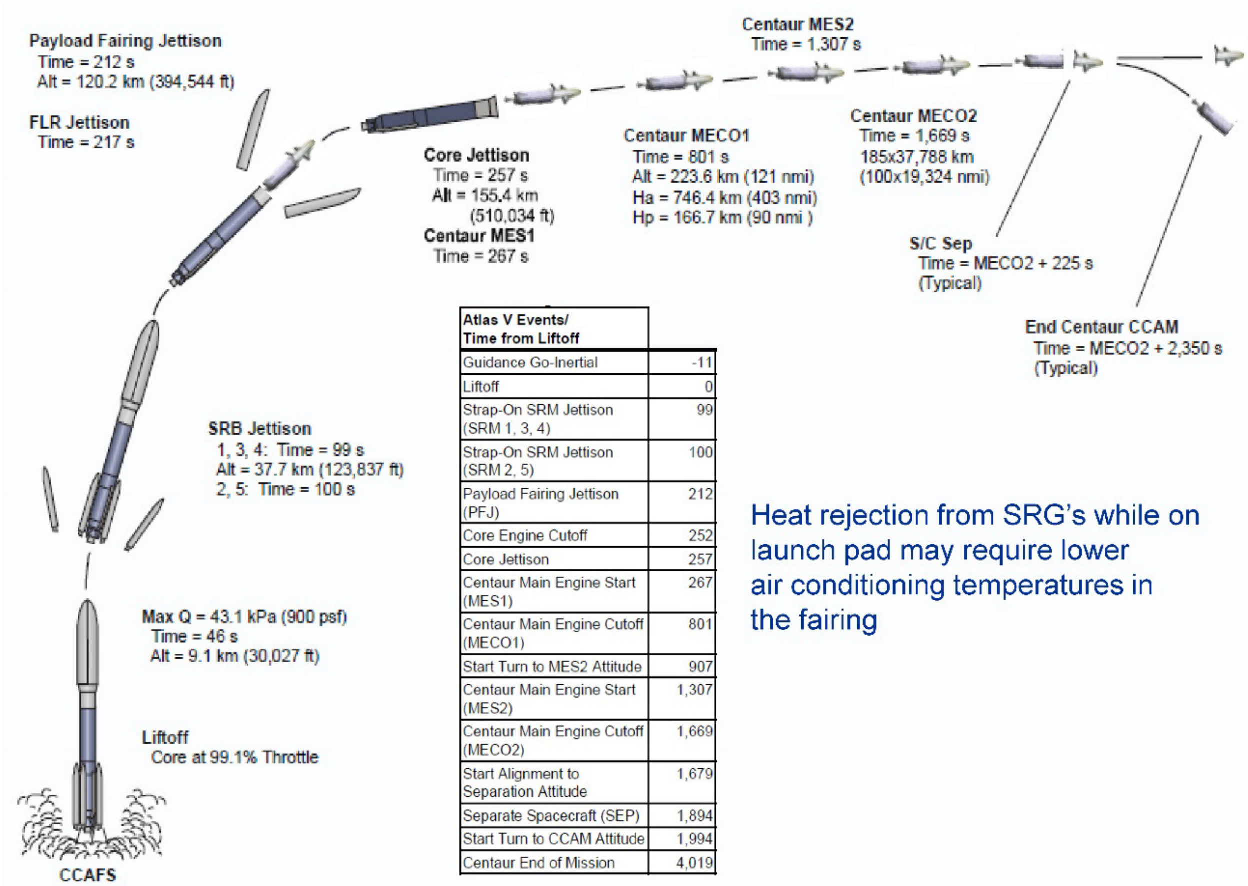


Figure 3.16.—LV ascent profile. (Image based on Figure 2.3-4 Typical Atlas V 551 GTO Ascent Profile, and Table 2.3-2 Typical Atlas V Mission Launch Vehicle Sequence Data, Atlas Launch System Mission Planner's Guide, Revision 9, September 2001. Used with permission from Lockheed Martin.)

3.2.3 Earth to Titan Cruise

After the TTI burn, the S/C is on a heliocentric trajectory which will eventually take it to the Saturn system and a direct insertion into the atmosphere of Titan. Planetary flybys and gravity assist maneuvers will be required to increase the S/C's velocity beyond that provided by the LV. The detailed trajectory design would be part of a Phase II study.

After separation from the LV, ranging is done to determine orbit parameters and create a state vector. The state vector will be used to determine the attitude and magnitude required for the first course correction burn to be performed by the S/C. Course correction burns are executed to compensate for LV injection errors.

Once on course, and between periods where planetary flybys will occur, the S/C will be placed in hibernation for the majority of the cruise phase except for times when pre-planned health assessments occur or when any trajectory correction maneuvers must be performed.

3.2.4 Titan Entry, Descent and Landing

On approach to Titan, the vehicle will be configured for atmospheric entry. Aero-surface checks will be conducted and the vehicle placed in the proper attitude for entry. Due to the significant time delay in radio communication between Earth and Titan, the submarine's computer will execute EDL autonomously.

The entry phase commences as the vehicle begins to encounter the uppermost regions of Titan’s atmosphere. The vehicle flies at a high angle of attack, allowing drag to reduce its speed. Entry navigation is performed using IMU-sensed inputs until atmospheric navigation data and/or radar system navigation data become available. Attitude control is maintained using the RCS thrusters only until the aerodynamic control surfaces become effective; then, a blend of aero-surface and RCS control is used until control is able to be performed exclusively by the aero-surfaces.

Atmosphere data probes are deployed following the entry heat pulse. Flight control gains will be adjusted based on atmospheric and radar data. Entry guidance will modulate angle of attack and bank angle to control g-load, heat pulse, and landing footprint. The IMU's serve as the navigation sensors. Once the atmosphere is thick enough to produce lift, the vehicle is banked steeply, but without reducing the angle of attack. The bank leads to a slow course deviation which allows the flight path to be lengthened in order to manage energy. This also causes the vehicle to move off course and that leads to a “roll reversal”. Depending on the energy that is left there will be a few more rolls. Due to the shape of the generated flight path, these repeated turns/rolls are also known as “S turns”.

Throughout the Entry the onboard computer keeps track and constantly updates the flight path and the required maneuvers are executed. At approximately 760 m/sec (2,500 ft/sec) entry velocity, guidance steers the vehicle to tangency with a navigation-derived heading alignment cylinder projection, which intersects the final landing approach trajectory. During the circle, the vehicle’s altitude drops to about 3,048 m (10,000 ft) as it begins to align for landing. Radar data compared against prior data of Kraken Mare are used to refine its landing pattern.

The vehicle lines up with approach corridor at an altitude of approximately 3,048 m (10,000 ft) Approach speed is controlled by speed brakes. The approach corridor and landing location will be chosen such that the vehicle comes to a halt near the center of Kraken Mare. At around 610 m (2,000 ft) altitude, the vehicle changes its glide slope from a steep dive to a shallow glide slope all the way to touchdown on the surface of Kraken Mare. Such water landings using lifting bodies has been tested and proven by NASA Langley tests of STS models. (Figure 3.17).

Figure 3.17.—Shuttle water landing testing.

Taking advantage of ground effect, the vehicle touches down on the surface of the Mare at a sink rate no greater than 3 m/s (9.8 ft/s). Once at relative stop, the flight computer will enable the sub's phased array and omni antennas, and its propulsion system. Vents in the aerovehicle will be opened to flood the vehicle and the top half of the fuselage will be separated. Retention latch assemblies will open and umbilical connections between the sub and the aerovehicle will be severed or retracted. Alignment guides will assure a clean separation of the aerovehicle from the sub as it sinks beneath the surface of Kraken Mare. Fuselage separation system and time of separation (shortly before or after splashdown) would be assessed in more detail as part of a Phase II study.

3.2.5 Kraken Mare Exploration

3.2.5.1 Sub Commissioning

Once afloat, the sub will deploy the mast with the X-band omni antennas, the MET and the surface imaging system. Using Sun sensor data, the sub will obtain a lock on Earth so it can communicate its position and health status via one of the omni antennas. A low-rate beacon will be activated. The retention latch assemblies may be separated from the sub since they are no longer required.

During its first communications to Earth after landing, the submarine will:

- Play back entry-decent-splashdown (EDS) data
- Play back system-wide housekeeping data
- Return first measurements of wind speed, air and sea temps, sea state, sea current speed from the MET
- Return the first images from Kraken Mare
- Perform a health check to assess hull integrity and system-wide thermal balance

The sub will activate is depth sonar and track the aerovehicle as it sinks to the bottom of Kraken Mare, providing the first measurements of subsurface currents as well as the first indication of the local depth of the Mare.

Contact with Earth will last for approximately 16 hr. Before the end of the contact period, the sub will be commanded into a safe hold, listening for communications with Earth via one of the X-band omni antennas. During these periods through the course of the mission, several different holding patterns while out of contact with Earth may be evaluated. The sub could be instructed to drive at a slow speed in a box pattern, gathering data until time has elapsed until Earth acquisition. The sub could hold relative position and perform meteorological measurements, sea composition and current measurements. Once contact with Earth is re-established via the omni, the phased array antenna could then be used to relay science data gathered.

On the next day the submarine will run through sea trials to commission the submarine for operations (Figure 3.18). The propulsors will be run at low speed and any vibration feedback monitored. During this time there is no expectation of making headway. Once the low speed testing is complete, the propulsion system will be fully engaged and the sub will begin surface driving. Steady-state surface travel will include sonar tracking of the bottom to determine depth variation across the Mare. IMU calibration will also be done. Wind speed, air and sea temps, sea state, sea current speed (MET) data will be taken, as well.

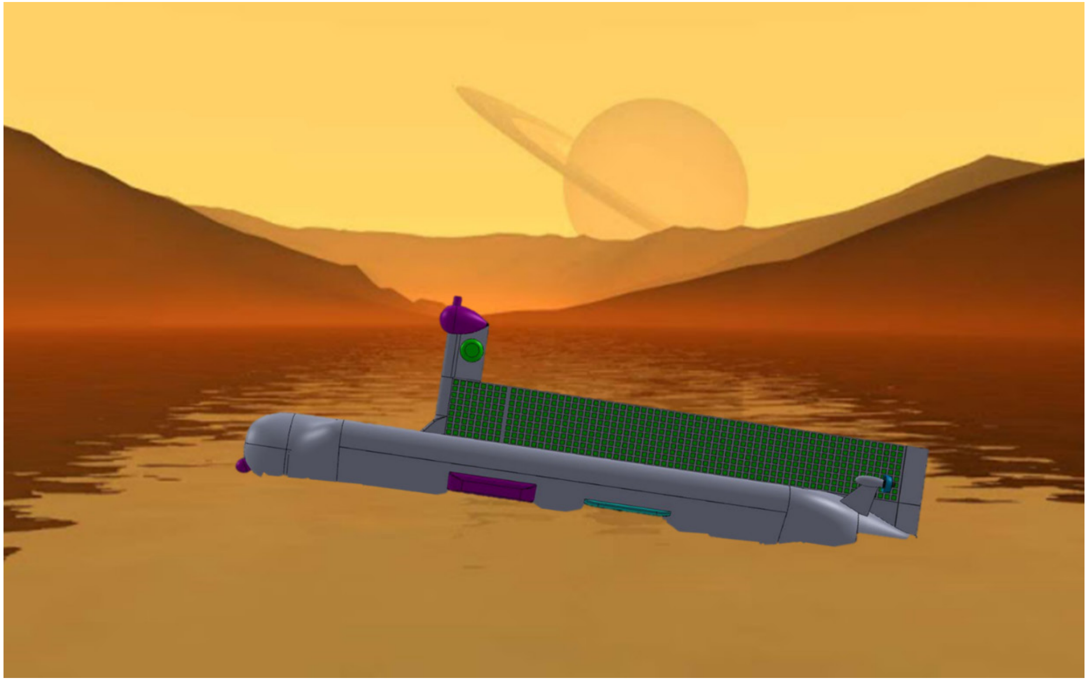


Figure 3.18.—Day 2 Sea Trials: Titan Submarine driving on the surface of Kraken Mare.

Days three and four will proceed to the next level of sea trials. A maximum drive speed test will be done to determine controllability of the submarine. Maximum surface speed is 0.9 m/s (3 ft/s), assuming 100W propulsion power. The limit on the surface speed is due to the power available to the propulsors. The lion share of power available from the SRG's is required for the communications system. An emergency stop test will also be done to assess controllability of the sub. The minimum speed that the sub can sail at while maintaining positive steerage will also be assessed.

After surface trials are complete, diving and surfacing trials will begin. The sub will be instructed to submerge and surface using the propulsors. A moderate dive/surface angle of the sub body of 10° would result in a rate of depth change of 0.17 m/s (0.6 ft/s). Once submerged, undersea driving would be done at a maximum submerged speed of 1.6 m/s (5.2 ft/s). The subs main computer would autonomously determination the trim required for undersea driving.

3.2.5.2 First Transit

With the final commissioning tests complete, the sub would begin its first leg of transit on its scientific mission. The first submerged leg of the transit would be limited to approximately 2 hr. Periodic sonar and liquid composition measurements would be taken and bottom sampling accomplished. The sub would then surface and reestablish contact with Earth via the DSN. A quick-look at the first long-duration transit would be done on Earth to verify that all was well on the sub, and then the sub would continue underway.

The first shoreline imaging would be conducted during the initial transit (Figure 3.19). The initial transit would cover approximately 200 km (124 mi) over a period of 61.7 hr of continuous propulsor operation taking 7 Earth days with 16 hr of downlink each Earth day. Atmospheric sensing and weather measurements by meteorology sensors would be gathered during surface driving.

Figure 3.19.—Shoreline imaging during the first transit of the Titan Submarine.

3.2.5.3 Primary Mission

The next leg of the primary mission would transit the sub 400 km (248 mi) over a period of 14 Earth days to the estuary of Ligeia Labyrinth. The goal is to 'sniff' whether there is a composition gradient driven by methane-rich flow from Ligeia. The sub would remain in the area through 24 Earth days (1.5 Titan days) of tidal monitoring to see how the cycle repeats. During the period, the sub would perform small transits and returns, then drift for a few hours at a time and measure displacement via imaging and sonar.

With the measurements at Ligeia complete, the sub would transit over a 14 Earth day period through Kraken Mare around the shoreline of Mayda Insula. The sub would perform detailed shoreline imaging, detailed bottom mapping and periodic bottom sampling.

Continuing along the shoreline, the sub would then perform tidal monitoring in a Strait for another 14 Earth day period (Figure 3.20). The sub would stay in the strait for a tidal cycle, performing small transits and returns followed by a drift of a few hours at a time to measure displacement via imaging/sonar. Detailed bottom mapping, detailed shoreline imaging (both mainland and islands) and periodic bottom sampling would be conducted.

The sub would proceed to the Throat of Kraken and would loiter in the area for a 14 Earth day period. Once again, the sub would remain in the strait area for a tidal cycle. Small transits and returns are performed, and then the sub would drift for a few hours at a time and measure displacement via imaging/sonar. Detailed bottom mapping and periodic bottom sampling would be done, as well as detailed shoreline imaging. This would represent the end of the sub's 90 day primary mission but it would still have substantial power available to continue its explorations for extended missions.

During an extended ninety day mission, the submarine would transit the throat of Kraken and perform similar explorations in other areas of Kraken Mare. Once this half year of exploration is completed the submarine could be tasked to revisit points of interest and perhaps do a complete sonar mapping of the seas. All in all, the submarine could explore over 3,000 km (1,864 mi) at an average speed of 0.3 m/s.

At some point, though, the output of the submarine's power plants would reach a level where sea travel is no longer feasible and it would truly reach its EOM state (Figure 3.21). The sub would be run aground so that the nuclear material in the SRG's remains contained within the sub. This would mitigate the risk of the sub sinking to a depth where the hull could be compromised and nuclear material could be released into the Mare.

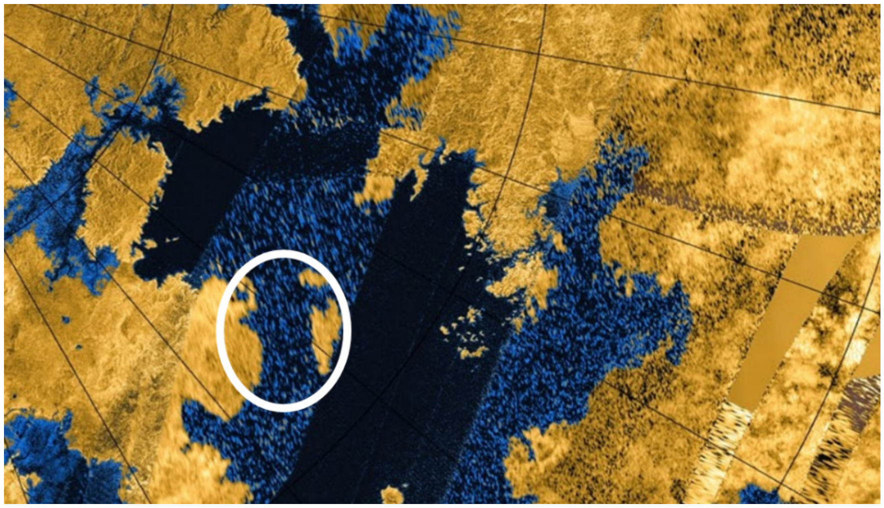


Figure 3.20.—Investigating Bayta Fretum Strait to the south of Mayda Insula.

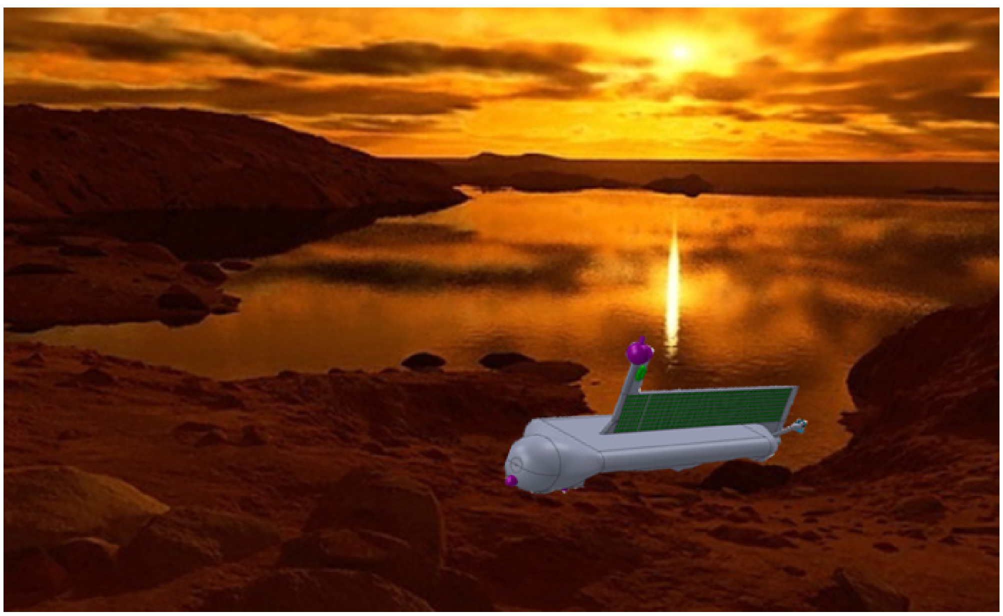


Figure 3.21.—The Titan Submarine is grounded when mission is complete.

3.2.5.4 Fail Safe Modes

The communications delay between Earth and Titan will necessitate a high degree of autonomy in the sub's flight computer. The distance from Earth to Titan can vary from 8 to 11 AU (1 AU = 149,661,688 km (93,000,000 mi)). Therefore, round trip communications between Earth and Titan can vary from 67 to 92 min. Sortie plans (surface or submerged) will be uplinked to the sub and verified before a sortie is executed.

During moving or stationary surface operations the sub communicates with Earth through the phased array antenna for high data-rate communications. Surface transits must be planned accordingly so that one side of the array can maintain Earth lock. If communications is lost, the sub will go to "All Stop" and use Sun sensor data to position the sub to re-acquire Earth via one of the X-band omni antennas.

During a dive operation, submerged sortie or surfacing operation, the sub may be out of contact with Earth. If an off-nominal situation occurs, the sub will surface and acquire Earth communications via an X-band omni antenna.

3.2.5.5 Operations Risks

Operations risks would be assessed in detail, and mitigation plans developed in a Phase II study. These risks include, but would not necessarily be limited to:

- LV failure resulting in Earth atmospheric entry of S/C and SRGs
- TTI insertion failure
- Failure during planetary flyby resulting in loss of S/C or loss of mission
- Aerovehicle does not survive Titan atmospheric entry
  - Thermal protection system failure
- Aerovehicle splashdown loads are higher than anticipated resulting in lateral loads on the aerovehicle and sub that are beyond design limits
- Guidance failure resulting in:
  - Failure of aerovehicle to survive Titan atmospheric entry
  - Higher than anticipated lateral loads on aerovehicle and sub during splashdown
  - Failed landing on Titan
- Aerovehicle vents fail to open and vehicle does not sink beneath sub
- Aerovehicle fuselage separation fails
- Sub hull integrity compromised

4.0 Subsystem Breakdown

4.1 Communications

4.1.1 Cruise Stage/Lifting Body Communications Analysis

The mission analysis for the trans-Saturn cruise and Titan EDL phases of the mission were noted but not developed in the Phase I concept. They will be assessed in a Phase II Study.

4.1.2 Communications Requirements

The Titan Submarine's communications requirement is to provide a direct science data downlink to Earth for data processing and analysis. The submarine will have to endure a cryogenic environment on the Titan surface while exploring Kraken Mare. External submarine hardware will have to endure, then operate after exposure to temperatures approaching minus 180 °C (93 K). For the case of the communications system, the phased array antenna is the external hardware. The DTE data requirement is 500 bps through the Deep Space Network (DSN), 16 hr per day while surfaced.

4.1.3 Communications Assumptions

For this design it is assumed that the only component of the communications system exposed to the external cryogenic hydrocarbon environment is the phased array antennas. All other components are contained within the submarine interior structure maintained at a nominal Earthlike room temperature environment. Further assumptions are a standard 3 dB communications link margin for the link budget. This is a typical margin for space design applications. This design does not use a space relay to Earth. All communications are assumed direct Titan to Earth. The link budget was sized for 8.5 AU Titan to Earth range. Simulations show this will be the approximate Titan to Earth distance in 2038, which is the earliest projected arrival date of the Titan Submarine. X-band deep space communications and phased array antennas will be used for Titan science data downlink to Earth due to the higher available gain of the phased arrays and low aerodynamic drag on the submarine as compared to a dish. High gain low profile

omnidirectional antennas will be used for an emergency beacon and communications. A total of 330 W have been allocated for the communications system on a 24 V DC S/C bus. A 34 m DPN Earth station antenna will be used for downlink communication. This is a single fault tolerant design.

4.1.4 Communications Design and MEL

Due to the distance between Titan and Earth, the required survivability of communications external assets in a cryogenic environment, and the need for a low profile external structure to reduce drag on the submarine while submerged, the Titan to Earth direct data downlink is a major design driver for the Titan Submarine system. Although Ka-band would be very attractive due to the higher bandwidth and data rate capabilities, the water vapor in the Earth's atmosphere would significantly attenuate a Ka-band receive signal as compared to either S-band or X-band. Also, because of the narrower beam characteristics of Ka-band, the antenna pointing must be more accurate as compared to X-band and S-band. Titan submarine platform control could add to the uncertainty in pointing accuracy due to stability and the projected inherent low Titan to Earth elevation angles (minimum 15° to 30° above horizon in year 2040+, maximum 41° in 2049 as seen from 75 N, Kraken). Therefore, X-band was chosen because the data throughput matches or exceeds other comparable use bands in throughput for the same size antenna, with minimal impact from atmospheric water vapor absorption. Also, the X-band is already compatible with the DSN, and has heritage use and specific frequency allocations for deep space applications with less frequency crowding as compared to S-band. A phased array antenna was chosen for electronically steerable pointing and to get a high amount of gain per mass and lower drag surface area than a dish antenna enclosed within a dome. The phased array antenna surface area available was 4- by 0.5-m. The antenna was partitioned into 3.5- by 0.5-m for data transmission and 0.5- by 0.5-m for receive. The transmit link budget was analyzed using a conservative 40 dBi phased array antenna gain. This gain was determined by using an upper bound of the maximum achievable gain for 3.5 m dish antenna of approximately 45 dBi and phased array antenna gain of approximately 10log10N + Patch Element Gain (~5 dBi for patch and 10 dBi for horn) for nominal 4096 elements, or approximately 41.12 dBi. Above a certain number of phased array elements, the degradation due to path loss and other capacitance effects outweighs the achievable gain, and could actually result in a gain decrease. Two phased array antennas, one on each side of the fin, will be used in this design.

The design also includes two high gain omnidirectional antennas, one on each side of the instrument mast. These antennas will be used for emergency, very low bit rate communications or a ranging "I'm alive" signal.

The analysis used Titan atmospheric effects of approximately 0.6 dB for atmospheric attenuation and 0.1 dB for surface diffraction.

The Small Deep Space Transponder (SDST) at X-band was chosen as the transmitter for this design (Figure 4.1) The SDST is configurable and could be modified to accommodate necessary parameters to ensure mission success, including proper coding and modulation. It also has a built in beacon mode for ranging and emergency communications.

To develop the amount of RF energy required to close the data link budget, a traveling wave tube amplifier (TWTA) and associated electronic power conditioner were chosen. Current X-band TWTA technology can generate RF power between 25 to 165 W with 55 to 65 percent efficiency. Using the conservative estimate of 55 percent efficiency, this is approximately 300 W DC, which fits within the current power budget and will also allow the communications link to close and validate. An example of the TWTA and associated EPC are included in Figure 4.2.

The mass of all of the components of the communications system are included in the MEL shown in Table 4.1.

Figure 4.1.—X-Band Small Deep Space Transponder.

Figure 4.2.—TWTA and EPC hardware.

TABLE 4.1.—COMMUNICATIONS SYSTEM MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Communications and Tracking	--	-----	26.3	16.0	4.2	30.5
X Band	--	-----	26.3	16.0	4.2	30.5
X band TWTA	1	1.00	1.0	5.0	0.1	1.1
X band EPC for TWTA	1	1.20	1.2	5.0	0.1	1.3
Phased Array	2	9.00	18.0	20.0	3.6	21.6
Coupler	2	0.20	0.4	5.0	0.0	0.4
Diplexer	2	0.30	0.6	5.0	0.0	0.6
Deep Space Transceiver	2	2.00	4.0	10.0	0.4	4.4
Connections	1	0.50	0.5	5.0	0.0	0.5
Phased Array Enclosure	0	60.00	0.0	10.0	0.0	0.0
X-band Omni Antenna	2	0.30	0.6	5.0	0.0	0.6

4.1.5 Communications System Analysis

Figure 4.3 shows that the communications link between Titan and Earth is feasible at the required data rate, given the previous assumptions.

4.2 Command and Data Handling (C&DH) System

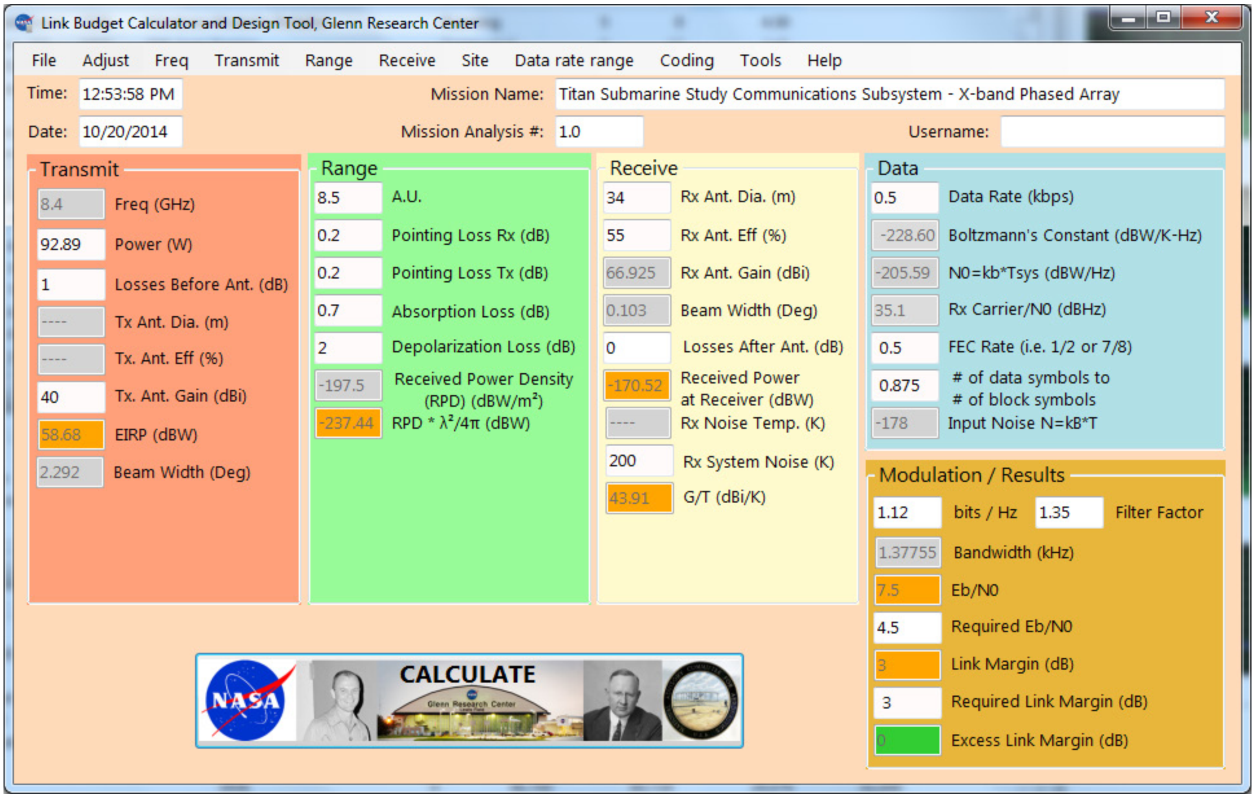
The C&DH subsystem is used to provide computer control and data storage for the submarine and the aerovehicle carrying it to Titan.

4.2.1 C&DH Requirements

The C&DH System provide the processing capability and data storage to operate the equipment on the Titan submarine and its aerovehicle through all phases of the mission. The system concept has a single fault tolerant main processor rated for 50 krad total dose radiation environment. The system has a science data storage capability large enough to accommodate 25Mb/day.

4.2.2 C&DH Assumptions

The C&DH enclosure will be inside the pressure shell of the submarine and will be maintained in a temperature environment of 280 K.



X-band ....8.2 to 8.5 GHz
RF Output Power................49 dBm (92.89 W)
Maximum Data Rate..........................0.5 kbps
Range ....Up to 8.5 AU
Required Link Margin ....3 dB
Uncertainty Link Margin...........................3 dB

Figure 4.3.—Titan Submarine communication link analysis.

4.2.3 C&DH Design and MEL

The concept design solution includes a flight controller enclosure populated with electronic boards selected based on their capability to meet mission goals and to survive the environmental conditions. The main components are:

- Two processor cards utilizing Power PC 750 radiation hardened cards, or equivalent.
- Watchdog switcher.
- Solid state memory card.
- cPCI enclosure with power supply.
- Atomic Clock module/Ultra oscillator module.
- Valve/Compressor drivers.
- Data interface cards (RS422/485) for communications, science and navigation instruments.
- Wiring harness and connectors.

The system concept is illustrated in Figure 4.4, and the C&DH MEL is shown in Table 4.2.

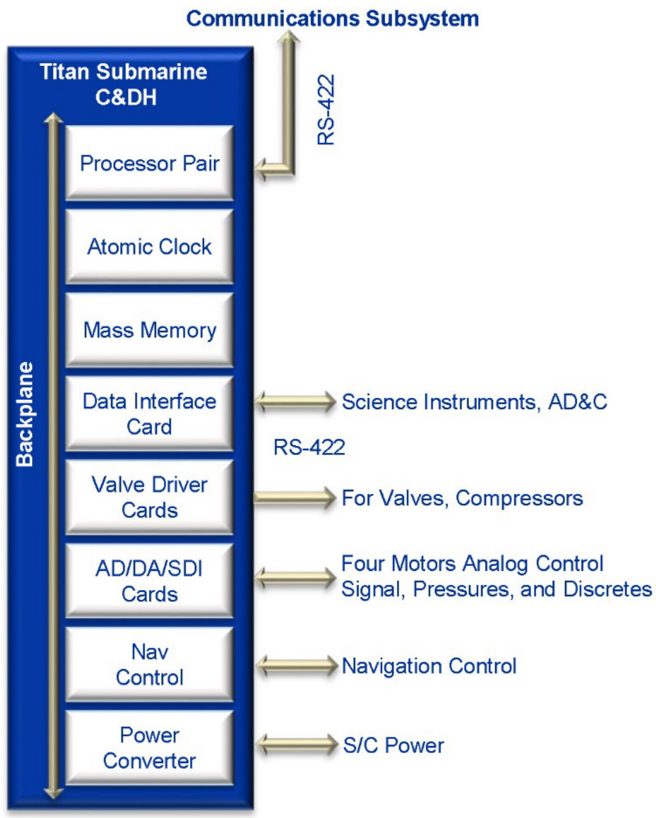


Figure 4.4.—Titan Submarine C&DH System.

TABLE 4.2.—C&DH SYSTEM MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
C&DH	--	------	44.0	30.0	13.2	57.2
C&DH Hardware	--	------	30.0	30.0	9.0	39.0
Flight Controller	1	30.00	30.0	30.0	9.0	39.0
Instrumentation and Wiring	--	------	14.0	30.0	4.2	18.2
Data Cabling	1	14.00	14.0	30.0	4.2	18.2

4.3 Navigation

4.3.1 Requirements

The requirements for the Navigation design were as follows:

- The design must be single fault tolerant
- Point the phased array antenna to Earth for communication phase
- Estimate the vehicle position, velocity and attitude throughout the mission, beginning after Splashdown on Titan.

4.3.2 Assumptions

It was assumed that the position updates obtained by being tracked by ground stations on Earth are accurate to ~ 1 km. (0.6 mi). Cassini, currently in orbit around Saturn, is tracked to approximately this accuracy.

4.3.3 Design Summary

4.3.3.1 Position Updates

Position updates are obtained in between successive submerged operations while the vehicle is on the surface. A Sun sensing camera is used to obtain the direction to the Sun. Using ephemeris stored in the onboard computer, the direction to the Earth is then calculated, and the vehicle is then oriented such that the phased array antenna is pointed towards Earth for communications. The vehicle obtains updates to its position and heading during this phase. A reasonable estimate on the expected accuracy for a position fix while on the surface is approximately 1 km. Cassini, currently in orbit around Saturn, is tracked to approximately this accuracy. Terrain imaging, while the submarine is surfaced and near the coast, may also aid in position determination, comparing images taken by the SI to those stored on board.

4.3.3.2 Submerged Navigation

Submerged navigation is accomplished with a sonar and Doppler Velocity Log (DVL) aided Inertial Navigation System (INS). The Navigation MEL can be seen in Table 4.3.

In general, an INS calculates position, velocity and attitude using data from an IMU, which consists of three accelerometers and three gyros. Over time, if not updated, errors in the IMU build up and the state estimates begin to drift further and further from the true values. To reduce the growth in error, redundant sensor measurements are integrated with the INS through a Kalman filter. The redundant measurements, in this case, are supplied by a low drift DVL and imaging sonar. The DVL tracks the velocity of the vehicle relative to the sea bottom, and while it aids in position measurement, does experience a drift in position error, mostly in the direction along the sub’s track. The sonar improves navigation accuracy by taking successive images of the sea bottom to estimate the vehicle’s bottom relative velocity. The navigation components can be seen in Figure 4.5.

TABLE 4.3.—NAVIGATION MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
AD&C	--	----	32.9	18.0	5.9	38.8
GN&C	--	----	32.9	18.0	5.9	38.8
IMU	2	8.50	17.0	18.0	3.1	20.1
DVL	2	4.30	8.6	18.0	1.5	10.1
Sun Sensor	2	1.00	2.0	18.0	0.4	2.4
Sonar Transducer	2	1.40	2.8	18.0	0.5	3.3
Sonar Electronics Module	1	2.50	2.5	18.0	0.5	3.0

Kearfott KN-5050 IMU Teledyne DVL Moog Side Scan Sonar

Figure 4.5.—INS Components.

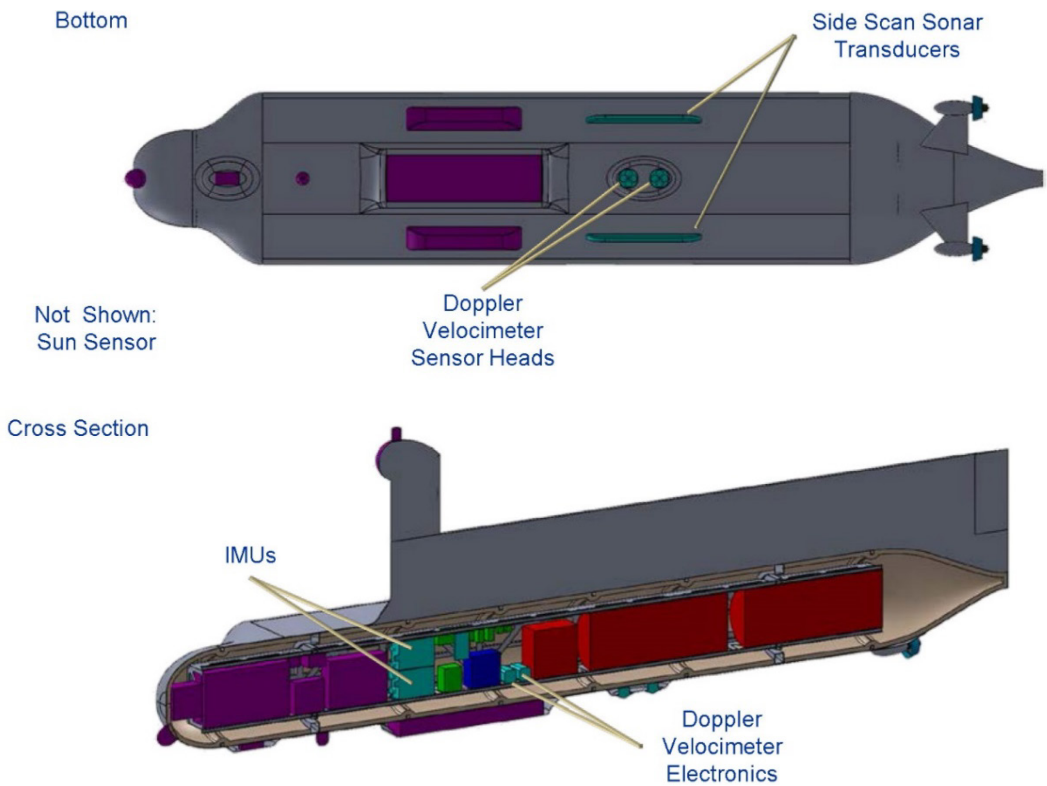


Figure 4.6.—Location of navigation components.

Modern INS systems are capable of heading drift rates of less than 0.01°/hr. Assuming the distance traveled in 8 hr of submerged operations is approximately 20 km (12 mi) (average velocity between 0.5 and 1 m/s (1.6 and 3.3 ft/s)), this would correspond to an error in position of less than 10 m (33 ft). Modern systems also employ a magnetic compass, which provides the capability to essentially estimate vehicle heading continuously. This capability will not be possible on the Titan submarine, as Titan does not exhibit a magnetic field, hence the error in position would likely be greater for the Titan submarine. However, the expected growth of the error in position in 8 hr of submerged operations is still expected to be less than 1 km (0.6 mi). Taking into account the initial error in position of 1 km (0.6 mi) from being tracked by Earth, the total error in position after 8 hr of submerged navigation should be less than 2 km (1.2 mi).

To comply with the requirement of being single fault tolerant, two of each of the navigation components were included in the design, with the exception of the side scanning sonar. A side scanning sonar is also held in the Science MEL, and could be used should the navigation sonar fail. The locations of the navigation components can be seen in Figure 4.6.

4.3.4 Trades

The following were the various options considered for submerged navigation.

4.3.4.1 Long Baseline (LBL)

LBL systems provide accurate autonomous underwater vehicle (AUV) position measurements once a network of LBL transponders has been deployed and calibrated. LBL systems offer very high position accuracy and position stability, sometimes as good as < 1 m (3.3 ft) error in position, however it does require transponders to be moored to the sea floor with high position accuracy. While this option does offer high accuracy in position estimation, it would require the deployment of transponders that would each need to be independently powered, as the Titan Submarine moves through Kraken Mare.

4.3.4.2 Sonar and DVL Aided INS

This option was ultimately chosen for submerged navigation. It does not require having a separate vehicle to be in communication with Earth, nor does it require the deployment of transponders.

4.3.5 Recommendation

One recommendation would be to construct a 3 degrees of freedom (DOF) simulation of the submerged operations, modeling all sensor errors. This would give an idea of the best possible navigation accuracy that could possibly be achieved during submerged operations.

4.4 Buoyancy Control System

The buoyancy control system for the Titan submarine is used to enable the submarine to float on the surface of the seas, descend into the sea in a controlled manner and then resurface again. This is accomplished by utilizing pressurized Ne gas and control valves to channel in either the liquid methane or atmospheric nitrogen depending on the maneuver the submarine is taking.

The buoyancy system is required to operate from the surface to a depth of 1 km (0.6 mi) or more. The system consists of two external tanks, as shown in Figure 4.7.

These tanks can be vented to the atmosphere or filled with liquid methane to adjust the buoyancy of the vehicle. Smaller Ne pressurized tanks are located within the buoyancy tanks to control both pressure within the tank and depth of the vehicle. The Ne is used as a means of adjusting the liquid volume within the main tanks to set the vehicles buoyancy.

4.4.1 Buoyancy Gas Options

One of the first steps in designing the buoyancy system for the submarine was to select a buoyancy gas to provide the lift needed to surface and remain on the surface for as much time as desired. Three options were initially considered:

- Utilizing atmospheric nitrogen gas as the buoyancy gas
- Boiling the liquid methane to provide buoyancy
- Utilizing a contained inert gas (Ne) to provide buoyance.

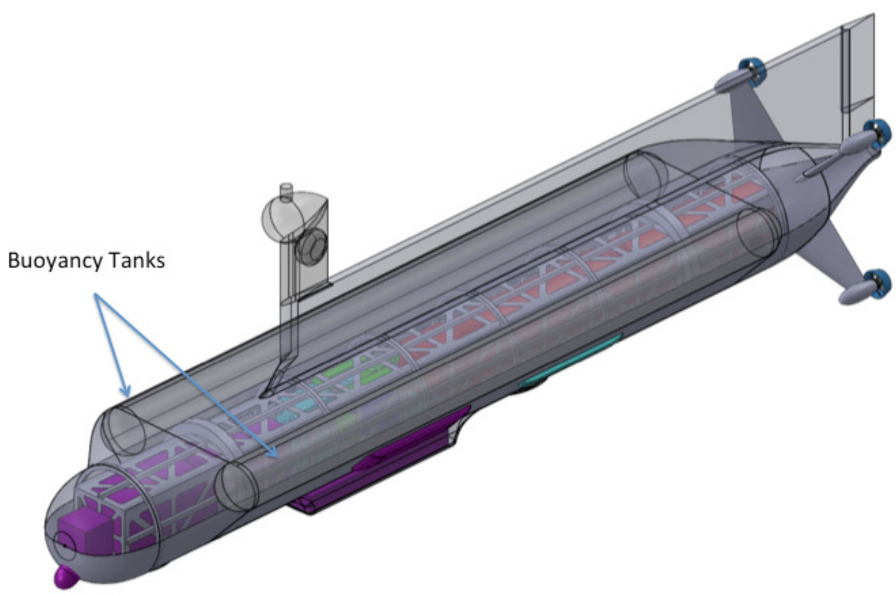


Figure 4.7.—Illustration of the buoyancy tank location.

Of these three approaches the third was selected as the best option for providing buoyancy in the submarine. At first it would seem that gathering and compressing the atmospheric nitrogen would be the best choice for generating buoyancy. However, upon further investigation it turned out that utilizing nitrogen would limit the depth which the submarine could reach. This is because nitrogen is condensable at the Titan operation temperatures and would liquefy at the temperature and pressure that would be experienced at a particular critical depth in the sea. This can be seen from the pressure-temperature diagram for nitrogen shown in Figure 4.8.

At the ambient temperature within the methane sea of 94 K, the nitrogen gas will liquefy as it is pressurized. This then limits the pressure to which the gas can be compressed and in turn limits the depth to which the submarine can descend. Using nitrogen as the buoyancy gas would limit the submarine depth to approximately 200 m (656 ft). Additionally, pressure control near the saturation point of nitrogen would be problematic, due to phase change of the gas.

To achieve greater depth another method would have to be utilized. Another option considered was to use the waste heat from the power system to boil the liquid methane and use this gaseous methane to fill the buoyancy tank. However, a thermal analysis on the heat required to boil the required amount of liquid methane quickly determined that there was insufficient waste heat available for this approach to work.

Based on this, a third option was devised that would enable the submarine to achieve greater depths and provide the buoyancy needed to return to the surface. This method utilized Ne as the buoyancy gas. Neon was selected since it is inert and will not react with the liquid methane. Also at the ambient temperature of 94 K it will remain gaseous even at high pressures, as shown in Figure 4.8.

4.4.2 Buoyancy Approach

To make the Ne gas buoyancy approach work, the Ne gas will need to be conserved between each ascent and descent. This requires the gas to be captured after ascent and repressurized prior to the next ascent. To accommodate these requirements, a system was devised that utilized a Ne gas pressure tank, control valves, and a piston all housed within the main buoyancy tanks. This arrangement is illustrated in Figure 4.9.

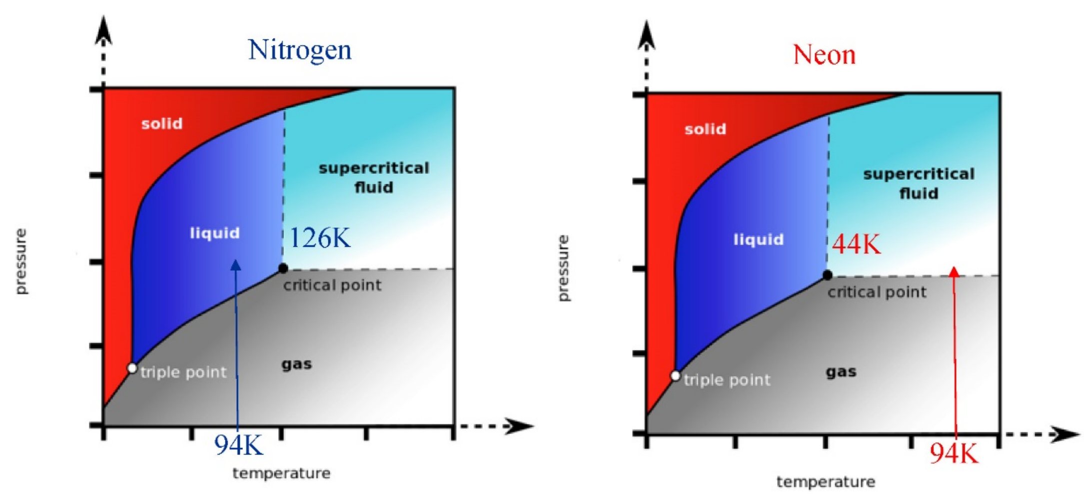


Figure 4.8.—Pressure-temperature diagram for nitrogen and neon.

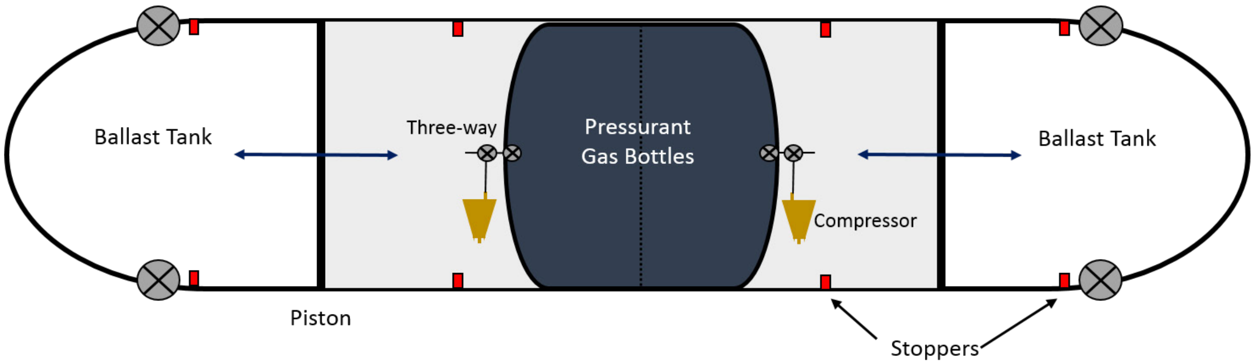


Figure 4.9.—Buoyancy tank layout.

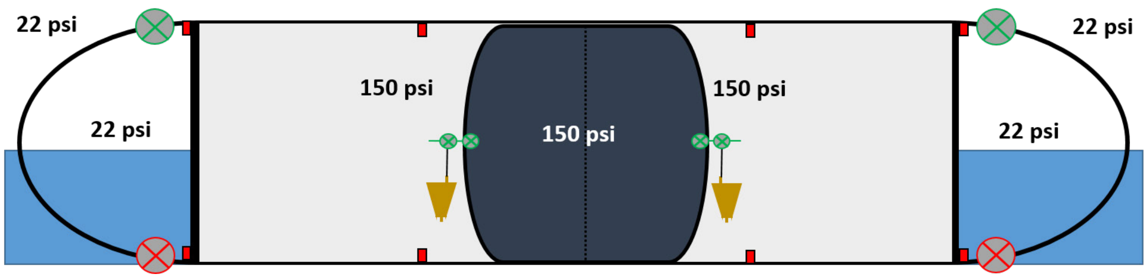


Figure 4.10.—Buoyancy configuration at the surface.

The buoyancy tank consists of a large outer cylindrical tank separated into front and rear halves. The tanks are symmetric about this center axis. At the center of the tank are the Ne pressure tanks. On either side of the Ne tanks is a piston that can travel the length of the cylindrical portion of the ballast tank up to the spherical ends. There are stops placed near the Ne tanks and the cylindrical ends to limit the range of the piston motion. There are four control valves that regulate the flow of liquid methane and atmospheric nitrogen into and out of the buoyancy tanks. There are also control valves and a compressor that regulate the flow of the compressed Ne into and out of the Ne pressure tanks. Utilizing these components, the operation of the buoyancy system is described from the following sequence.

The mass of the buoyancy control system's components can be found within the MEL for the TCS in Section 0.

4.4.2.1 At the Surface

Beginning at the surface, the pistons are fully extended up against the stops at the spherical portions of the tank. The main buoyancy tank body is filled with Ne gas at a pressure of approximately 1.03 MPa (150 psi), which is the approximate hydrostatic pressure at the lowest desired depth. On the buoyancy tank, the lower control valves, exposed to the liquid methane are closed and the upper control valves exposed to the atmosphere are open. This configuration is illustrated in Figure 4.10.

In this arrangement the submarine is buoyant and will float on the surface of the methane sea. The next step is to prepare the submarine for its next descent.

4.4.2.2 Preparing for Descent

While on the surface, operations such as data gathering and communications are taking place. It is estimated that the surface operations will require approximately 8 to 10 hr. Therefore during this time the submarine is preparing for its next descent. This is accomplished by pumping the Ne gas back into the Ne pressure tank, going from the 1.03 MPa (150 psi) when it filled the buoyancy tank to 6.9 MPa (1,000 psi) in the pressure tank. Since this pumping is done over an extended period of time the pump power required is

minimal (approximately 18 W). As the pressure tank fills up and the pressure drops in the buoyancy tank the pistons begin to move back toward the pressure tank to the original position. Once the pressure tank is full, the two pistons will be against the stops near the pressure tank and there will be a pressure of ~0.15 MPa (~22 psi) of nitrogen gas within the buoyancy tank. Atmospheric nitrogen flows into the buoyancy tank because the upper valves are open venting it to the atmosphere. The lower valves are still closed preventing the liquid methane from entering the tank. This configuration is illustrated in Figure 4.11.

In this arrangement the submarine is still buoyant and will float on the surface of the methane sea. Once in this configuration the submarine is ready to descend.

4.4.2.3 Descent Initiation

To initiate descent, the lower control valves at the bottom of the buoyancy tanks are opened. This allows liquid methane to flow into the buoyancy tank. The upper valves are also open allowing the nitrogen gas to escape as the buoyancy tanks fill with liquid methane. This configuration is illustrated in Figure 4.12.

In this arrangement the submarine will begin to descend. To control the descent, the top control valves can be closed, trapping the nitrogen gas within the tanks and slowing or stopping the descent. The ability to control or stop the descent will depend on how much variation there is in the density of the liquid methane with depth. If it does not vary much then the submarine will either sink to the bottom or float on the surface with little ability to control the depth. In that case the depth will need to be controlled actively by using the propulsion system to generate lift enabling the submarine to stay at a desired depth. If there is a small variation in the methane density with depth then the submarine can become neutrally buoyant at a given depth by controlling the release of nitrogen gas. This would work up to a depth of 200 m (656 ft) where the pressure would become too great and begin to liquefy the nitrogen. At depths below 200 m (656 ft) releasing some pressurized Ne, causing the pistons to move and expanding the Ne gas volume would be required to achieve a neutrally buoyant condition.

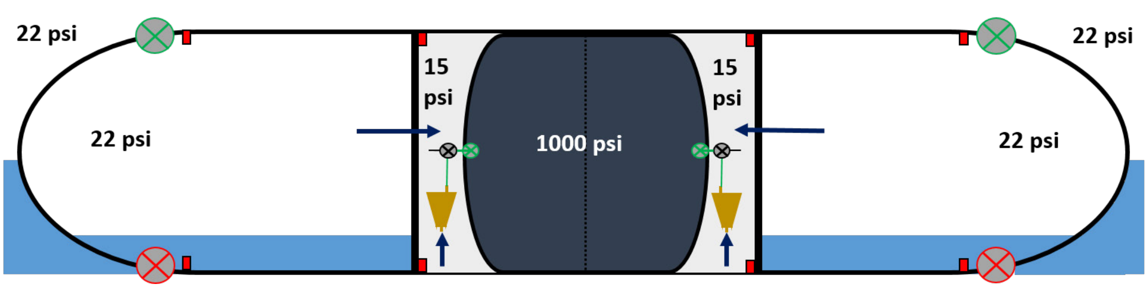


Figure 4.11.—Buoyancy configuration at the surface with the submarine prepared for descent.

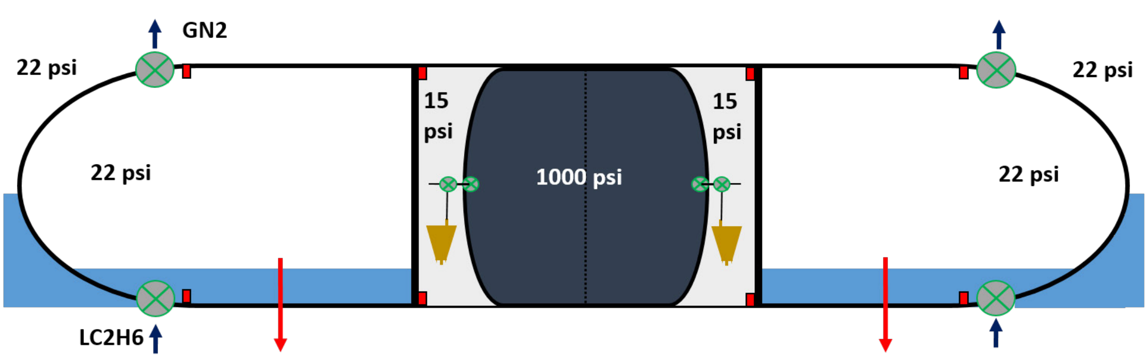


Figure 4.12.—Buoyancy configuration at the surface.

4.4.2.4 Neutrally Buoyant Operation

Once all of the nitrogen gas has left the buoyancy tank the submarine will descend to its maximum depth. This will be determined based on the weight of the submarine and its volume. As described previously, the depth of neutral buoyancy will depend on how the density of the methane varies with depth. If there is little to no variance then an active means of generating lift will be required to keep the submarine from descending beyond the desired depth. At this point once there is no nitrogen gas left in the buoyancy tanks, the upper and lower valves can be left open or closed. This configuration is illustrated in Figure 4.13.

4.4.2.5 Ascent

To begin the ascent, the upper control valves are opened. The valves from the Ne pressure tank are opened allowing the Ne gas to flow into the buoyancy tank and begin to move the piston toward the spherical end of the tank. As the piston moves the liquid methane is pushed out of the buoyancy tank through the upper control valve. At this stage the lower control valves can be either closed or opened. As the submarine nears the surface they will also be opened so that the liquid methane can flow out the bottom as the upper valves break the surface and are exposed to the atmosphere. This will prevent the spherical ends from staying filled with liquid methane when the submarine is on the surface. This configuration is illustrated in Figure 4.14.

Once the submarine reaches the surface it will be at the configuration shown in Figure 4.10 and the process can begin again.

4.5 Hydrodynamics and Propulsion (H/P)

A streamlined torpedo-like pressure hull is fitted with external cylindrical ballast tanks mounted high up on each side and covered with a free-flooded hydrodynamic fairing. Four fixed fins are mounted near the tail in an X configuration to provide hydrodynamic stability. Additional floatation and static ballast are distributed to provide hydrostatic stability. Small electric thrusters attached to the tip of each stabilizer fin provide propulsion, the thrust levels of each may be controlled independently to provide directional control, as shown in Figure 4.15.

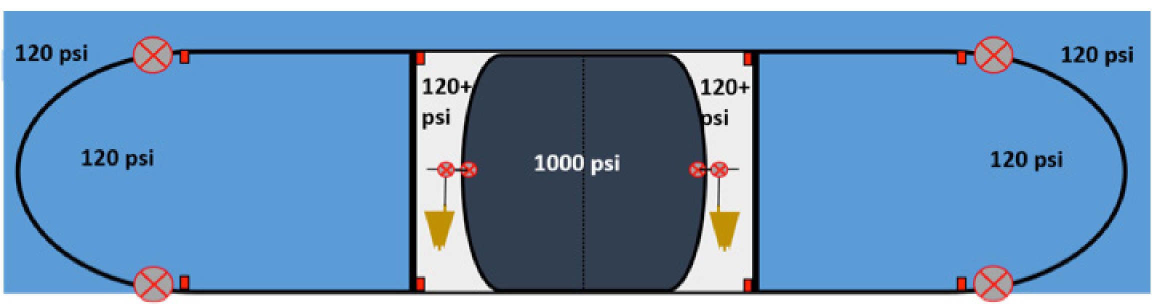


Figure 4.13.—Buoyancy configuration at the surface.

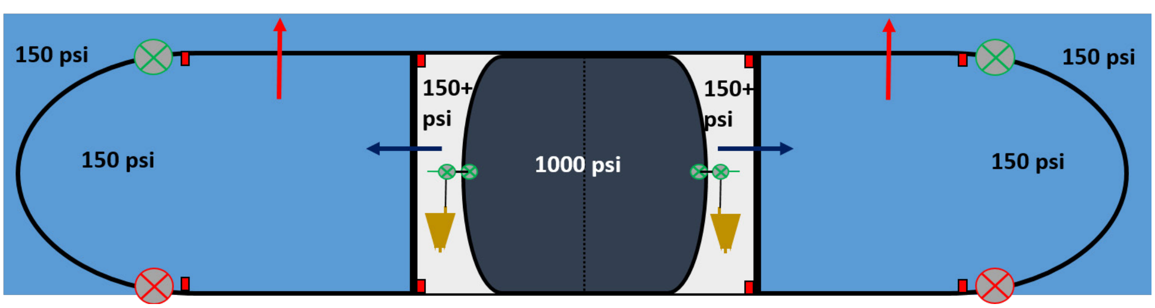


Figure 4.14.—Buoyancy configuration at the surface.

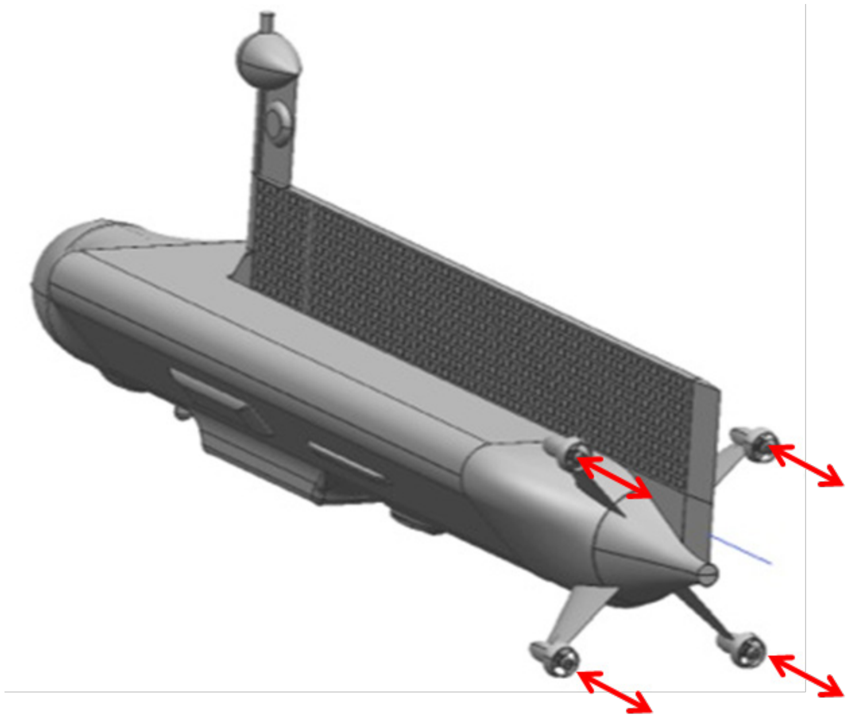


Figure 4.15.—Titan Submarine Propulsion System.

4.5.1 H/P Requirements

The Titan Submarine must be able to maneuver and transit both on and below the surface of Titan's Kraken Mare, a sea composed of cryogenic liquid hydrocarbons. The submarine will have a submerged transit speed of at least 1 m/s while consuming no more than 440 W of electrical power for propulsion. The maximum surfaced speed is not specified, but it should be able provide reasonable heading control while consuming no more than 100 W. The submarine must also be a stable platform from which to perform scientific measurements and to communicate DTE.

The design of the propulsion and control system as well as that of the overall vehicle must support these requirements in an environment that is considerably different from that of Earth's oceans; the surface temperature of Kraken Mare is estimated to be 94 K, with a liquid density that is 2/3rds that of saltwater and gravitational acceleration 1/7th that of Earth.

4.5.2 H/P Assumptions

Fluid properties at the surface were assumed to be those of liquid ethane at 94 K and 0.15 MPa (1.5 bar.) The liquid density is assumed to be 660 kg/m^3 (41.2 lb/ft^3) and the kinematic viscosity of 6.06×10^{-6} Pa-s (147.6 lb/ft-hr) resulting in a Reynolds number that is 1/6th that of an identical submarine at the same speed in terrestrial saltwater. Small (roughly 1 m (3.3 ft) in length) terrestrial UUVs, such as the Remote Environmental Monitoring Units (REMUS) 100 (Ref. 5) operate at Reynolds numbers near 1×10^6, where the Titan Submarine will be at 1 m/s (3.3 ft/s). Based on Reynolds number similarity the primary physics governing vehicle control and propulsion will be similar to those we are familiar with on Earth.

The resistance analysis assumes turbulent flow over the hull, though at this Reynolds number there will be significant surface areas subject to laminar flow. Care will have to be taken to avoid flow separation in regions of laminar flow, and perhaps to force transition to turbulent flow at a certain location.

The stability and trim analysis assumes a CB located 5 percent of hull diameter above the CG, both of which are located 45 percent of hull length from the bow, which is a good design point for many terrestrial

UUVs. Hull lift and drag are based on Slender Body theory which is a good assumption for high speed performance. In the case of a low speed vehicle, such as this, fluid mechanics problems such as dynamic positioning, cross-flow drag, and the control of flow separation should be the subject of future work.

4.5.3 H/P Design and MEL

Propulsion and directional control are provided by four thrusters mounted to the tips of four fixed stabilizer fins arranged in an X-stern configuration. The thruster assemblies include a brushless electric motor, gear box, magnetic coupler, and a ducted propeller. The thruster mass and volume were based on commercially available thrusters (Ref. 6) used in terrestrial UUVs and Remotely Operated Vehicles (ROVs), low speed and usually tethered undersea robots). The thruster chosen and its thrust performance in seawater are shown in Figure 4.16. The thrust produced on Titan would be at least 1/3rd less due to the lower fluid density. A detailed design of the thruster rotor, duct, and motor is required to optimize performance for the Titan environment.

A listing of the various components in the Titan Submarine Propulsion system and their corresponding masses is shown in Table 4.4.

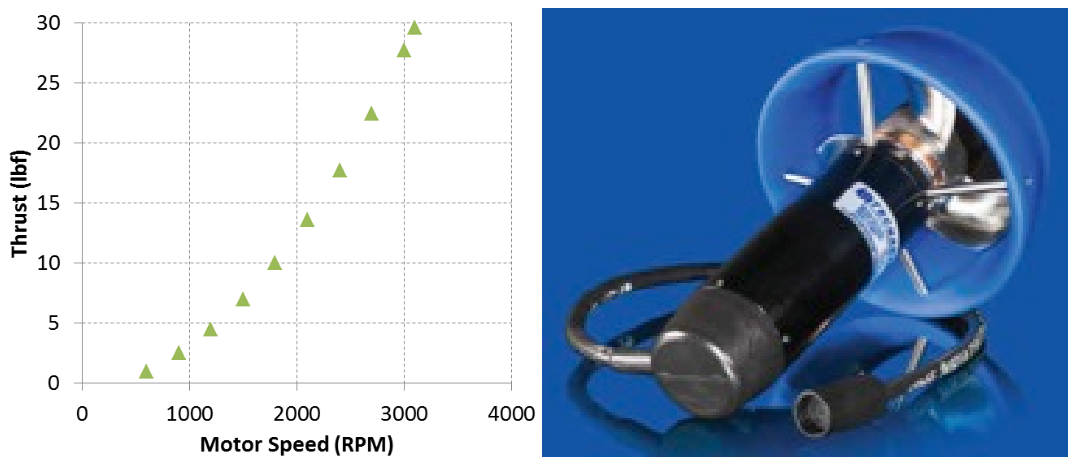


Figure 4.16.—Tecnadyne Model 560 performance.

TABLE 4.4.—PROPULSION AND CONTROL SYSTEM MASTER EQUIPMENT LIST

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Propulsion	--	-----	20.56	28.8	5.92	26.48
Main Propulsion System	--	-----	20.56	28.8	5.92	26.48
Main Engine Hardware	--	-----	20.56	28.8	5.92	26.48
Thruster	4	1.80	7.20	25.0	1.80	9.00
Thruster Controller	4	0.80	3.20	25.0	0.80	4.00
Thruster Housing	4	0.30	1.20	25.0	0.30	1.50
Stabilizer	4	1.48	5.92	25.0	1.48	7.40
Hardware	1	0.44	0.44	25.0	0.11	0.55
Thruster Cable	4	0.65	2.60	55.0	1.43	4.03

4.5.4 H/P System Trades

4.5.4.1 Vehicle and Propulsion System Trades

During a preliminary study several vehicle and propulsion system concepts were studied. The first configuration (Figure 4.17) was based on the Seahorse UUV, a terrestrial battery powered vehicle designed for long range survey missions at low speed. The Seahorse is propelled by a centerline mounted, ducted, swirl-canceling, high efficiency propulsor. Control authority is provided by moveable control fins placed in the propulsor jet to improve low speed maneuvering. The Seahorse was scaled to displace 1,000 kg (2,200 lbm) in ethane on Titan with a scale factor of 0.7. This concept exhibited good submerged performance, but lacked the ability to hover and the use of internal ballast tanks caused significant thermal management problems.

The second concept studied (Figure 4.18) was that of a Seahorse-like center body with two strut-mounted ballast tanks separated from the body by 10 cm (3.9 in.), due to concern that the liquid ethane contained within could vaporize due to waste heat emitted by the pressure hull. This design retained the tail mounted moveable control surfaces and propulsion came from thrusters mounted coaxially with the ballast tanks. This design featured improved surfaced stability due to vertically offset ballast tanks at the cost of added drag. Heading control at low speeds could be improved through differential thrust control, but pitch control could be problematic.

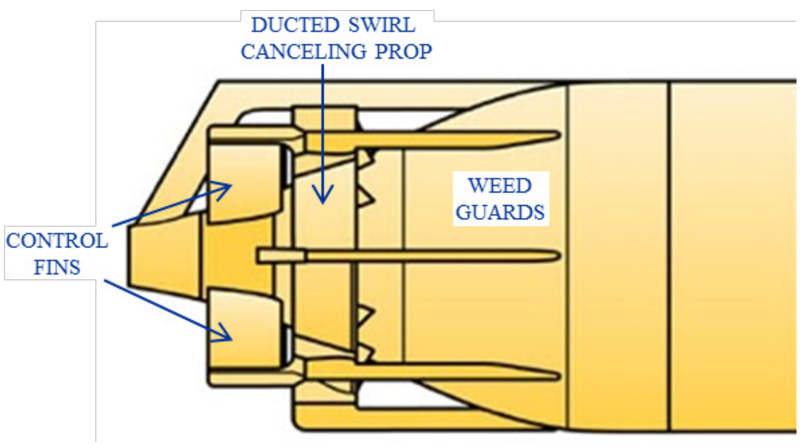


Figure 4.17.—Concept 1: Seahorse propulsor and control fins.

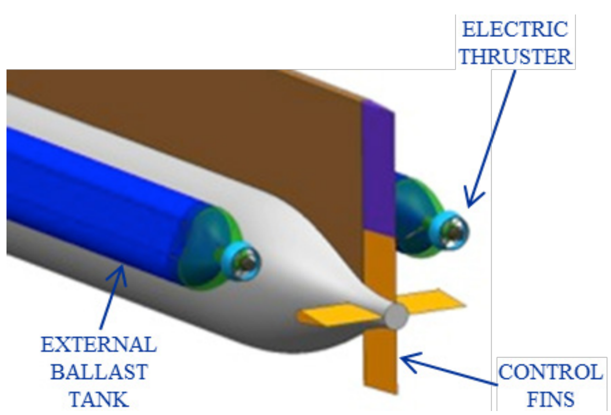


Figure 4.18.—Concept 2: External ballast tanks with electric thrusters.

It was determined by the thermal management team that separation of the ballast tanks and hull was not required, so the third design featured tanks adjacent to the pressure hull and enclosed by a hydrodynamic fairing (Figure 4.19). The sizes of the pressure hull and ballast tanks were adjusted to increase submerged displacement to 1,200 kg (2,646 lbm) (to reflect an increase in dry vehicle mass based on the latest MEL.) The requirement to load the SRGs on the launch pad drove the replacement of the moveable control fins on the tail by fixed stabilizer fins. Propulsion came from two thrusters mounted on moveable planes aligned with the drag axis of the vehicle to reduce the pitching moment due to propulsion. This design affected heading control with differential thrust and pitch control with thrust vectoring. This was the simplest and lightest configuration studied, however concerns about redundancy, the difficulty of locating plane actuators inside the hull near the SRGs, and ingestion of the atmosphere by the thrusters when driving on the surface remained.

The final evolution of the design moved the four fixed stabilizers forward on the tail and placed a thruster at each tip (Figure 4.20). No moveable control surfaces or actuators are required because pitch and heading control can now be affected by differential thrust, and the system is single fault tolerant when submerged. Surfaced propulsion and heading control are provided by the lower two thrusters only, eliminating the risk of atmospheric ingestion.

4.5.4.2 Stabilizer Trades

After the selection of Concept 4 an informal trade space study was conducted to examine the size, shape, position, and orientation of the fixed stabilizer fins. The stabilizer configuration was selected based on minimizing drag while maintaining infinite speed stability. The stabilizer arrangement is centered on the pressure hull centerline and spaced equally. Each stabilizer has a 12 percent thick NACA symmetric foil shape, swept leading edge, 1.6:1 aspect ratio, and planform area of 0.81 m^2.

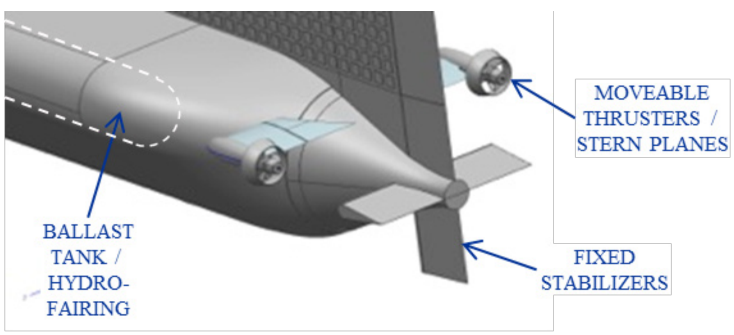


Figure 4.19.—Concept 3: Faired external ballast tanks with thrusters on stern planes.

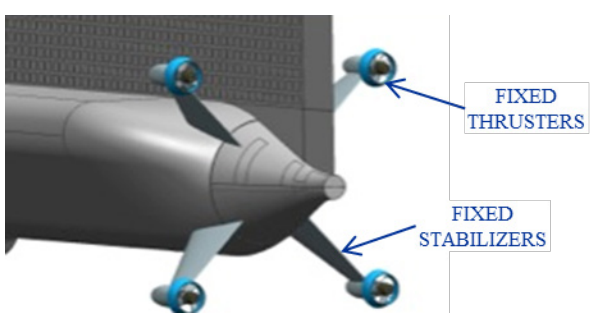


Figure 4.20.—Concept 4: Fixed stabilizers with tip mounted thrusters in X-stern configuration.

4.5.4.3 Thruster Trades

The means of generating thrust is a ducted propeller driven by an electric motor. Other concepts were explored in the preliminary design phase that utilized waste heat from the plutonium power source, including a resistojet (which develops thrust by heating and expelling a fluid or gas) and a conventional propeller operated by a turbine or similar means of converting steam into mechanical work. It was determined early in the design process that much of the thermal waste heat generated by the SRGs would have to be used to maintain the submarine's internal temperature, so a conventional electric motor and propeller combination was selected.

4.5.5 H/P System Analysis

4.5.5.1 Resistance Analysis

At the beginning of the preliminary design stage a propulsion system power estimate was made based on empirical relations for required flight power of propeller driven lighter-than-air vehicles on Earth which may be scaled to operate in the Titan submarine environment. It was shown by Lorenz (Ref. 7) that the installed power of an LTA vehicle (or a submarine) varies as

$$P = 3.0\ m^{0.6} V^{1.85} \left(\rho_{\mathrm{Titan}} / \rho_{\mathrm{Earth}}\right)^{0.33-0.5n}$$

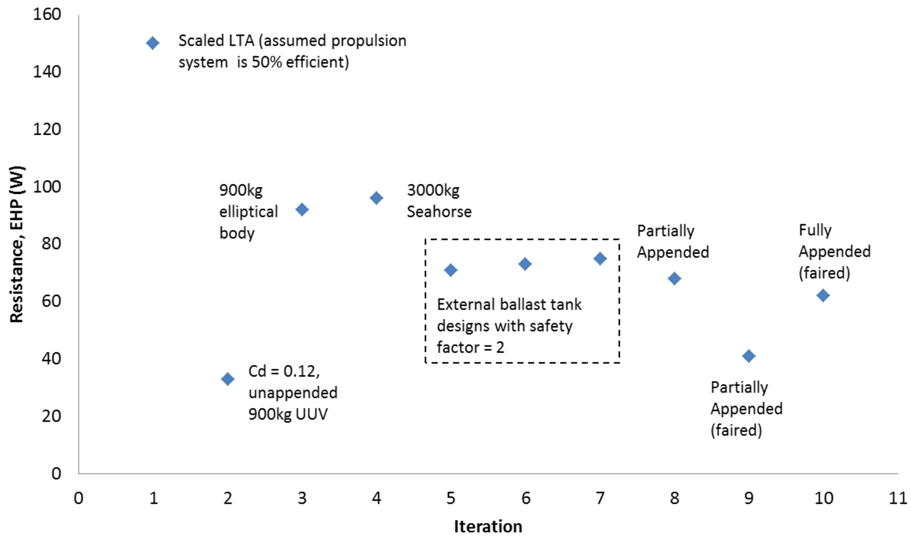
where m is the mass, V is the velocity, ρ is the fluid density, and n is a parameter representing the effect of density scaling on propulsive efficiency. With an initial value of $n = 0.5$, a 1,000 kg (2,205 lbm) submarine on Titan traveling 1 m/s might have an installed power of 300 W for the purposes of preliminary sizing. This estimate figured into the sizing of the power system, which in turn drove the diameter of the pressure hull.

The drag of non-streamlined objects appended to the hull was estimated using empirical models based on a collection of historical datasets (Ref. 8). Friction drag on streamlined shapes (hull, fins, streamlined appendages) was estimated using the ITTC 1957 model-ship correlation line which gives the coefficient of drag due to friction based on wetted area as a function of Reynolds number based on length:

$$Cf = \frac{0.075}{\left(\log_{10}\left(\mathrm{Re}_L\right) - 2\right)^2}$$

The skin friction drag coefficient was then multiplied by base drag and interference drag multipliers which are functions of the geometry (Ref. 9). These methods have predicted the resistance of terrestrial UUVs with complex appendages within 30 percent of that predicted by CFD-RANS. The impact of manufacturing imperfections such as gaps, steps, and fasteners was not studied during this phase. This method of estimating resistance was used in spreadsheet form during the early stages of analysis, and later in a MATLAB script that is used to predict the trim state of UUVs and other submerged streamlined vehicles. A history of the resistance estimates (shown as effective power to overcome drag in watts) made during the course of this study is shown in Figure 4.21, estimates 2 to 8 were multiplied by a safety factor of 2 to account for the effect of unknown appendages related to science collection and communications. The length and Reynolds number shown in the Reference Quantities are those of the final design.

The contribution of each component to the total vehicle drag for the final design at 1 m/s is shown in Table 4.5. The drag coefficient is based on a frontal area of 0.50 m^2. The input power is based on an assumed overall system efficiency of 51 percent.



Reference Quantities	
Speed (m/s)	1.0
Speed (kn)	1.9438
Diameter (ft)	2.6157
Area (ft^2)	5.3738
Fluid: Methane = 1, Ethane = 0	0
ρ (kg/m^3)	660.0
μ (Pa-s)	4.000×10^{-3}
ρ (slugs/ft^3)	1.288
ν (ft^2/sec)	6.488×10^{-5}
Length Scale (ft)	19.3
Reynolds Number	9.74×10^5
Accel due to gravity (ft/s^2)	4.435×10

Figure 4.21.—Empirical resistance estimates for vehicle concepts.

TABLE 4.5.—RESISTANCE AND POWERING ESTIMATE FOR FINAL DESIGN AT 1 m/s

Drag Breakdown		
Bare hull	3.28	23.5%
Fins	0.42	3.0%
Duct	0.17	1.2%
Antenna	0.95	6.8%
Struts	1.95	14.0%
EGVs	0.00	0.0%
Pods	1.72	12.3%
DS	0.79	5.7%
Bottom sampler	1.84	13.2%
P3 sensor	0.16	1.1%
Side scan sonar	0.10	0.7%
Sonar transducer	0.04	0.3%
Camera housing	0.13	1.0%
Camera mast	0.17	1.2%
Met. sensor	0.36	2.6%
Subsurface illumination	1.48	10.6%
Doppler velocimeter	0.19	1.4%
Omni-antenna	0.21	1.5%
Total drag, lbf	13.97	100.0%
$C_{D\_frontal\ area}$	0.3752	
EHP, hp	0.08	
EHP, W	62	
System efficiency, %	51	
Input power, W	122	

4.5.5.2 Powering Analysis

The efficiency of the propulsion system was estimated using an ARL Penn State propulsor sizing code used in the design of propellers for the U.S. Navy. A swirl-canceling ducted thruster having a propeller diameter of 0.27 m was evaluated, in seawater, at 1 m/s with a thrust of 50 percent of the total drag (assuming that two of the four thrusters will carry most of the load) and found to have a propulsive efficiency of 68 percent. Using common values found in industry for electric motor efficiency (80 percent), planetary gearbox efficiency (95 percent) and magnetic coupling efficiency (98 percent) it can be calculated that the total system efficiency is 51 percent. The assumption that propeller efficiency in seawater is the same as in liquid ethane will have to be validated in the next phase.

Using the previously calculated drag coefficient and propulsion system efficiency, and assuming that they do not change significantly over small changes in speed, one can calculate the performance of the submarine as shown in Table 4.6. Although Surfaced resistance varies from submerged resistance due to changes in pressure, friction, appendage, and wave making drag, for the purposes of a preliminary analysis we have assumed that they are equal. The maximum speed submerged, based on the 440 W available for propulsion, was 1.57 m/s. The maximum speed surfaced, based on the 100 W available for propulsion, was 0.93 m/s. Power consumption at the submerged design point of 1 m/s was 122 W.

4.5.5.3 Hydrodynamic Stability Analysis

Hydrodynamic stability of the final design was evaluated using a MATLAB code that calculates and plots the speed-dependent roots of the characteristic equations obtained from the standard submarine equations of motion (Refs. 10 and 11). The stability code also calculates and displays the “Infinite Speed” stability index, derived from the constant term in the characteristic equations when the hydrostatic moment is assumed to be “zero,” hence “Infinite Speed”. Results are given for the Vertical-Plane and Horizontal-Plane Motions, respectively. The roots are non-dimensional (i.e., Laplace Transform of the time variable) and are interpreted for the dynamic stability (Refs. 12 and 13). The geometry analyzed is shown in Figure 4.22 and the resulting code output in Table 4.7 for the design point of 1 m/s (3.3 ft/s), submerged, and neutrally buoyant. The results suggest that the handling characteristics will be benign. A sensitivity analysis to buoyancy was performed and stability was found to be insensitive to small changes in buoyancy (±5 percent).

TABLE 4.6.—SUBMERGED PROPULSION SYSTEM PERFORMANCE

System Efficiency = 51%			
Speed, m/s	Drag, lbf	EHP, W	Power, W
0.25	1.1	1	2
0.5	3.9	9	17
0.75	8.2	27	54
[a]0.93	12.3	51	100
1	14.0	62	122
1.25	21.1	118	230
1.5	29.7	198	388
[b]1.57	32.3	224	440

[a]Maximum surfaced speed; [b]Maximum submerged speed

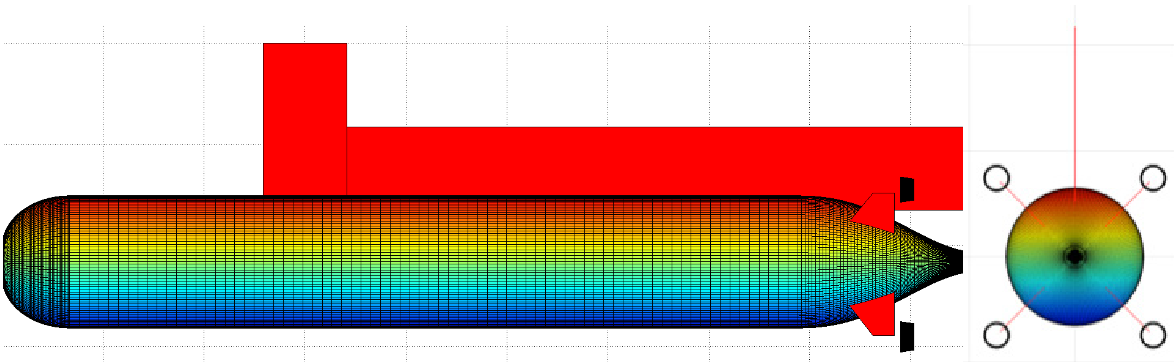


Figure 4.22.—Vehicle geometry analyzed in stability code.

TABLE 4.7.—STABILITY CODE OUTPUT AT 1 m/s, NEUTRALLY BUOYANT

Quantity	Value	Interpretation
Margin of stability, GV	0.24	Marginally stable
Vertical-plane stability roots	–0.12, –0.12, –0.12	Non-oscillatory (overdamped) stable
Vertical-plane damping ratio	1	Non-oscillatory, critically damped
Margin of stability, GH	0.50	Highly stable
Horizontal-plane stability roots	–4.39, –0.41	Oscillatory (underdamped) stable
Horizontal-plane damping ratio	1	Non-oscillatory, critically damped

4.5.5.4 Hydrostatic Stability Analysis

Hydrostatic stability of the final design was evaluated using a spreadsheet. Component locations and volumes from the CAD model and mass estimates (with component level growth) from the MEL supported the calculation of CB and CG. System level mass growth was added at the CM of the pressure hull. For the purposes of this analysis the acceptance criteria for hydrostatic stability was that the CB be above the CG at the same longitudinal location. All submarines require that this condition be maintained during all phases of submerged and surfaced operation, and a larger distance between CB and CG generally increases roll and pitch stability.

The baseline configuration was found to be unstable and top heavy, which is not unexpected given the relative size of the superstructure to the rest of the submarine. Extra displacement was added in the form of syntactic foam installed in the free flooded spaces between the ballast tanks and pressure hull (Figure 4.23). The preliminary baseline dry mass was 1,148 kg (2,531 lbm). The floatation provided 141 kg (311 lbm) of additional buoyancy and 34 kg (75 lbm) of mass. Subsequent calculation determined that 180 kg (397 lbm) of static ballast (usually in the form of lead bricks or pellets) was required at a location low in the keel and 2.1 m (6.9 ft) from the bow. The stable configuration has a dry mass of 1,361 kg (3,001 lbm). Six characteristic operating conditions are shown in Table 4.8 with the required ballast tank load, and resulting wet weight and CB/CG offset. The last condition, surfaced with full ballast tanks, is marginally unstable, but the vehicle is likely to submerge long before this condition is reached. It will be a goal of future design iterations to reduce the amount of static ballast required to stabilize the submarine through creative arrangement of the internal systems and mass reduction of the superstructure.

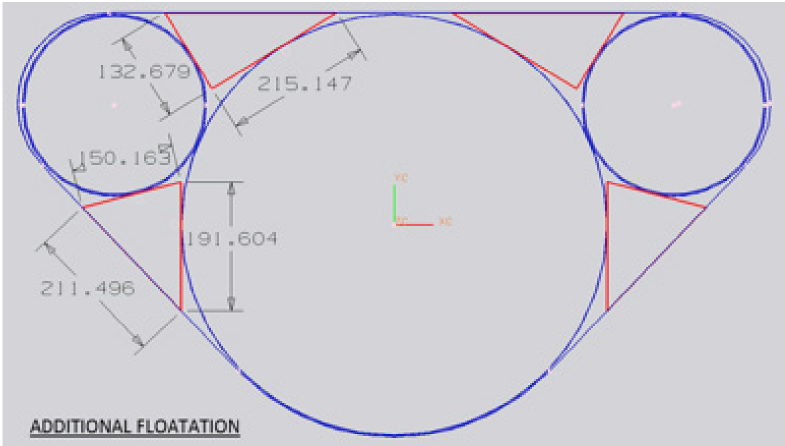


Figure 4.23.—Supplemental floatation and mass (dimensions are in mm).

TABLE 4.8.—HYDROSTATIC ANALYSIS RESULTS (DRY MASS = 1,361 kg (3,001 lbm))

State	Ballast Tank Volume, %Full	Wet Weight, kg	CB/CG Offset, mm
Submerged, neutral	77	0	21
Submerged, light	0	–220	66
Submerged, heavy	100	65	23
Surfaced, neutral	50	0	13
Surfaced, light	0	–189	43
Surfaced, heavy	100	96	0

The dry mass of the sub increased by 24 kg (53 lbm) after the hydrostatic stability analysis was complete. This change (~1.8 percent) would not affect the stability analysis significantly, unless the mass increase was concentrated high above the centerline of the vehicle. The hydrostatic analysis would be repeated as part of a Phase II study as the sub design is further refined.

4.5.6 H/P Risk Inputs

With four thrusters providing propulsion and directional control when submerged the failure of any single thruster can be tolerated. On the surface, the failure of one of the two submerged thrusters will leave the submarine with the ability to travel only in a circle. A failure of this type would not end the mission, as heading could still be controlled to facilitate communications with Earth by varying the shaft speed and direction of the single remaining thruster, but the risk to navigation from being unpropelled for 16 hr out of every 24 would have to be assessed. One way to mitigate this risk would be to install a transverse tunnel thruster near the bow to assist in maneuvering at the cost of increased mass and drag.

Knowledge of the working fluid properties is a critical input to the submarine design process, much more so than for a surface ship. A surface ship, for example, might be able to displace several times its own weight in water and thus be insensitive to small changes in fluid density. A submarine, due to the requirement to adjust buoyancy to submerge, typically displaces only 1.1 to 1.2 times its own weight in water when surfaced. If the liquid density of Kraken Mare is 20 percent greater or less than anticipated then the submarine would be unable to submerge or surface respectively. The uncertainty in density must be calculated and accommodated by the final design.

The reduction of cavitation is a design goal for many terrestrial pumps and propellers due to the noise, vibration, and erosion damage it causes. The risk of cavitation is low in pure ethane on Titan due to its low vapor pressure at 94 K and the high atmospheric pressure. There is a risk, however, that dissolved atmospheric nitrogen could bubble out of the ethane and cause a reduction in propulsive efficiency. The

concentration of dissolved nitrogen is expected to be 3 to 4 percent by mass (seawater at 1 Bar is 0.002 percent air by mass), the impact of which will need to be evaluated in the next phase.

If a single-use stabilizer deployment mechanism is required to accommodate the interior dimensions of the re-entry vehicle, then there is a risk that the failure of that mechanism would impact vehicle stability, propulsion, and maneuvering. Such a mechanism could be extensively tested during development to reduce that risk, and the stabilizers could be sized such that the system is single fault tolerant.

4.5.7 H/P Mobility Recommendation

The use of electric motor driven propellers in the form of strut mounted thrusters has been proposed for the propulsion and control of the Titan Submarine. It is recommended that a thruster be designed and analyzed using CFD to refine the estimate of propulsive efficiency in the Titan environment. An input to the design process will be an in-depth study of the impact of the dissolved nitrogen bubbling out of the ethane-rich sea. As part of the design study an electric motor and gearbox should be selected that are capable of operating in the cryogenic environment, as they are part of the overall efficiency estimate.

A study should be undertaken to quantify the effectiveness of the propulsion and control system in low-speed submerged maneuvering and hovering. The study should also examine the surfaced stability of the submarine, since roll stability and heading control will impact communication system performance.

It is further recommended that the next phase include a detailed design and analysis of the hydrodynamic fairings enclosing many of the scientific and communications protuberances, as these tend to drive the propulsion power requirement that is an input to the thruster design.

4.6 Electrical Power System

The Titan Submarine requires a system that can power the sub and aerovehicle for the transit from Earth to Titan, through Titan EDL and still provide power for at minimum 90 d surface mission (and preferably for multiple years afterward). Candidate power systems include both RPS, Fission Power System (FPS) and fuel cells. The FPS and RPS power systems are assumed to be modified versions of their deep space counterparts. Two, eight SRGs were selected as the power systems for this study.

4.6.1 Power Requirements

Power varies from 78 W at launch to 842 W during submarine activation and checkout as shown in Table 4.9. Average power requirements during multiday surface or subsurface cruise is about 800 W. Submarine bus voltage is 28 V (± 6) while nominal start of high power operations is 10 yr after launch (3 storage +7 transit). Titan mission duration is assumed to be 3 yr although nominal minimum mission duration is three months. Because of the long duration cruise at maximum power energy, storage is not used for power peaking. Because of the liquid ethane and methane sea temperature, heat rejection should be similar or superior to 4 K deep space operation for which most space power systems are designed.

TABLE 4.9.—TITAN SUBMARINE POWER REQUIREMENTS

Power modes, W									
1	2	3	4	5	6	7	8	9	10
Launch	Interplanetary Cruise	Titan EDL	Sub Activation and Checkout	Dive/ Surface	Submerged Cruise	Surface Cruise	Stationary Submerged Operations	Stationary Surface Operations	EOM Disposal
60 min	TBD Yr	2 hr	1 wk	TBD min	TBD d	TBD d	TBD d	TBD d	0.0
78	91	117	842	826	839	746	269	534	166

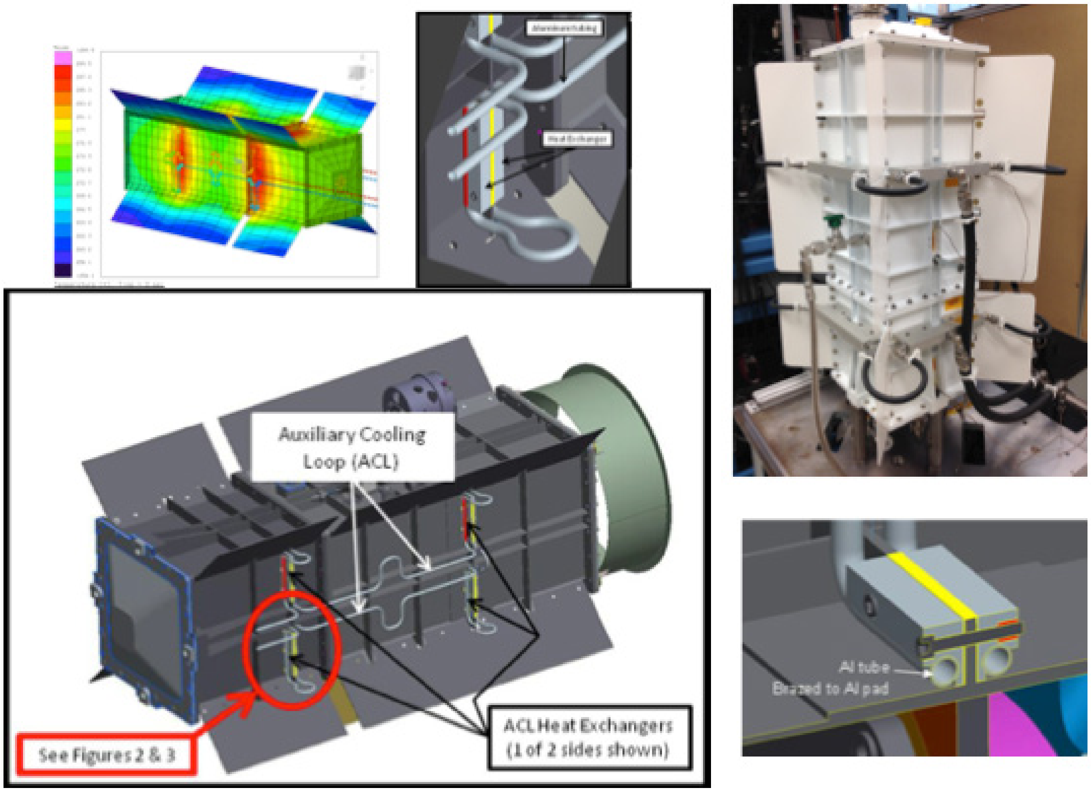


Figure 4.24.—SRG heat removal.

4.6.2 Power Assumptions

It is assumed that the power system is isolated from the liquid ethane/methane and contained within the submarine interior pressure vessel. Heat rejection to the environment is accomplished via a pumped loop system similar in design to the SRG Auxiliary Cooling System (ACS) for each of the candidate systems. Figure 4.24 shows the implementation of such a heat removal system that is currently being used for the SRG. Additionally it is assumed that the submarine is filled with 10 bars of dry nitrogen. Microporous solid insulation is used for all of the candidate power systems and while the 10 bars of dry nitrogen does increase the thermal conductivity of the insulation, the lower rejection temperature compensates for this additional heat leak (Ref. 14).

4.6.3 Power Design and MEL

The selected power system uses a pair of eight general purpose heat source (GPHS) SRGs. Recent work on the Nuclear Power Assessment Study resulted in four SRG designs with two, four, six, and eight GPHS, respectively. Because the Titan submarine requires 840 W 13 yr after fueling, two, eight GPHS SRG were chosen as the baseline power system proving 900 W of DC power. These eight GPHS SRG are derivatives of the SRG in as much as they consist of two Stirling convertors operating in a dual opposed configuration to minimize vibration. These convertors use a MarM-247 heater head with hot cycle temperatures of 760 °C. Rejector temperature is 120 °C at beginning of mission (BOM). Solid insulation

surrounds the GPHSs to drive the heat into the convertors. Each SRG is about 1 m (3.3 ft) long and 36 cm (1.2 ft) in diameter with a mass of 65 kg (143.3 lbm). Heat is removed via a pumped loop system attached to the radiator housing as discussed previously. Overall heat in to DC power conversion efficiency at beginning of life (BOL) is 25 percent. Further performance details can be found in Table 4.10. During the launch and transit a heat removal system similar to that used on the Mars Curiosity rover is assume with a pumped loop system removing heat to a radiator located on the lifting body/cruise stage. Heat load for the titan submarine is about 4,000 W; double that for the Curiosity Mars rover.

The two SRGs are connected to the S/C bus and provide 26 (±6 V). Figure 4.25 shows the electrical architecture. Each SRG has its own shunt if no power is being drawn from the unit, just as in the SRG. An S/C shunt balances S/C power requirements and power generated from the SRGs. Additionally, a 6,000 µF bus capacitance via a 1 kg (2.2 lbm) lithium ion battery is required to help control voltage fluctuations. This battery is bookkept under the PMAD for the sub.

All of the components of the power subsystem and their masses are shown in Table 4.11.

TABLE 4.10.—CANDIDATE SRG

Number of GPHS	2	4	6	8
CBE Inputs				
BOL (4 K), W	130	240	370	510
BOM (4 K + BOL + 3 yr), W	126	232	357	492
EOM (4 K BOL+10 yr), W	104	193	297	450
BOL (270 K), W	116	215	331	456
BOM (270 K), W	113	207	319	440
EOM (270 K), W	93	173	266	366
Degradation rate, %	1.16	1.16	1.16	1.16
Diameter, cm	19	33	33	36
Length, cm	50	45	65	95
GPHS heat load (BOL), W *	500	1000	1500	2000
GPHS heat load (EOL), W	437	874	1312	1749
Controller efficiency, %	90	90	90	90
BOL waste heat (4 K), W	356	733	1089	1433
BOL Stirling cold end temperature (4 K), K	420	450	450	430
Average heat rejection temperature (4 K), K	400	428	428	408
Average heat rejection temperature (270 K), K	440	468	468	448
Disturbance force (at 100 Hz)	10	13.6	16.9	19.8
BOL specific power, W/kg	7.5	7.5	7.9	7.9
Mass, kg	17.3	32.0	46.8	64.6
BOL efficiency, %	26.0	24.0	24.7	25.5
EOM efficiency, %	23.8	22.1	22.6	23.4

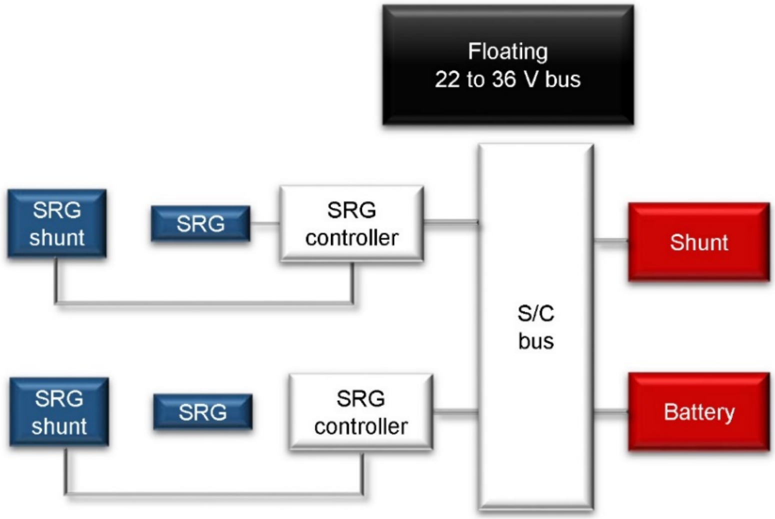


Figure 4.25.—Titan Submarine Electrical Architecture.

TABLE 4.11.—POWER SYSTEM MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Electrical Power Subsystem	--	-------	146.0	20.0	29.2	175.2
Power Generation	--	-------	130.0	20.0	26.0	156.0
Miscellaneous 06.1.5.a.a	2	65.00	130.0	20.0	26.0	156.0
PMAD	--	-------	16.0	20.0	3.2	19.2
Miscellaneous 06.1.5.b.a	1	16.00	16.0	20.0	3.2	19.2

4.6.4 Power Trades

Four candidate power systems were considered for the Titan submarine. The first was a FPS using a derivative of the 1 kWe Kilopower reactor coupled to eight Stirling Convertors. This FPS concept design (Figure 4.26) is a current NASA and DOE joint project designed to leverage the Advanced Stirling Convertors (ASCs) used in the SRG and couple the reactor to the Stirling convertor with heat pipes. While compelling because of the scarcity of Pu-238 it was not selected as the designs produce a higher mass system than an RPS. Estimates for the Kilopower FPS reactor, shield and power conversion are around 400 kg. A secondary option considered was to use the liquid methane in a fuel cell to generate electrical power. A high temperature solid oxide fuel cell (SOFC) with direct methane reformation was considered as an option with the Earth delivered oxidizer being O_2 in the form of lithium perchlorate candles. These are the same O_2 supplies used on the International Space Station as emergency backup. Unfortunately due to the long duration and relatively high power over 1700 kg of candle mass alone was need to supply 800 W for 90 days. Next, Multi-Mission Radioisotope Generator (approximately eight needed for the 750 W of power) were considered power source candidates. Because of their high plutonium consumption (6 percent conversion efficiency), low specific power (2.7 W/kg) and high degradation rates (3.8 percent power loss per year) they were not considered as viable candidates. SRG based upon the convertors developed for the SRG were selected as the baseline power system. Each of these convertors uses eight GPHS modules and provide about 450 W at EOM. Two generators were required for the Titan submarine. These generators have high specific power (>7 W/kg), high overall conversion efficiency (>27 percent heat in to DC power output) and relatively low degradation rates (1.2 percent per year).

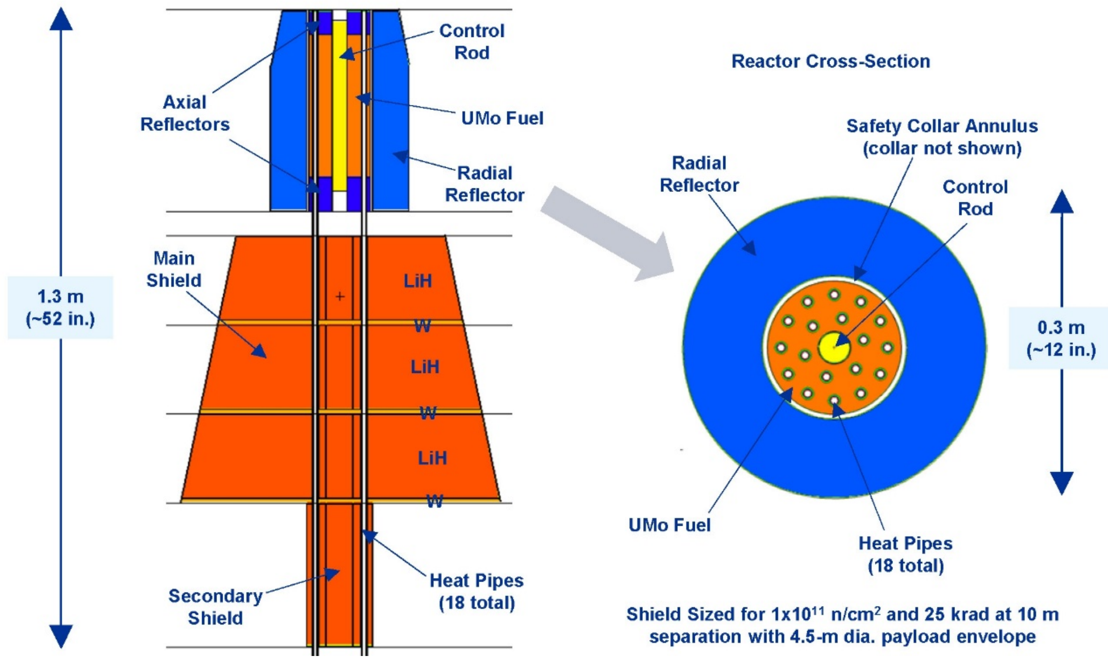


Figure 4.26.—Kilopower reactor and shield.

4.7 Thermal Control

The main purpose of the TCS for the Titan submarine mission is to balance the heat generated by the isotope power system with the heat losses to the environment. The thermal system design will include devising an approach to maintain the internal components of the submarine within their desired temperature operating range. Based on this design an estimated the mass, size and any power requirements for the thermal system components will be made.

4.7.1 Vehicle Operational Environment

The operating environment of the submarine is within the liquid methane and ethane seas of Titan. However, the submarine internal components will also need to survive the transit through deep space from Earth to Titan.

The harsh environment of Titan provides a number of challenges in the operation of equipment and materials. Operating within this environment, from entry to descent to the liquid methane and ethane seas requires a thermal balance between the heat generated by the isotope power system and the losses to the environment which is accomplished through thermal insulation and distribution of the heat generated. To accurately size the thermal system, the operational environment throughout each phase of the mission must be defined.

The environmental conditions on Titan are very unique and unlike those on any other known planet or moon. In some ways, though, it is very Earth like. It has a mostly nitrogen atmosphere, clouds, lakes, rivers and rain. However, with a surface temperature of under 100 K the free liquid is not water but methane. The low atmospheric temperature also lowers the speed of sound through the atmosphere. Near the surface the speed of sound is approximately half that on Earth. Due to the distance from the Sun, cloud cover and haze, little sunlight reaches the surface. The atmospheric density at the surface is 5 times that of Earth and the pressure is 1.5 times greater than that at Earth's surface. A diagram of the atmosphere is shown in Figure 4.27 and select properties of Titan are given in Table 4.12.

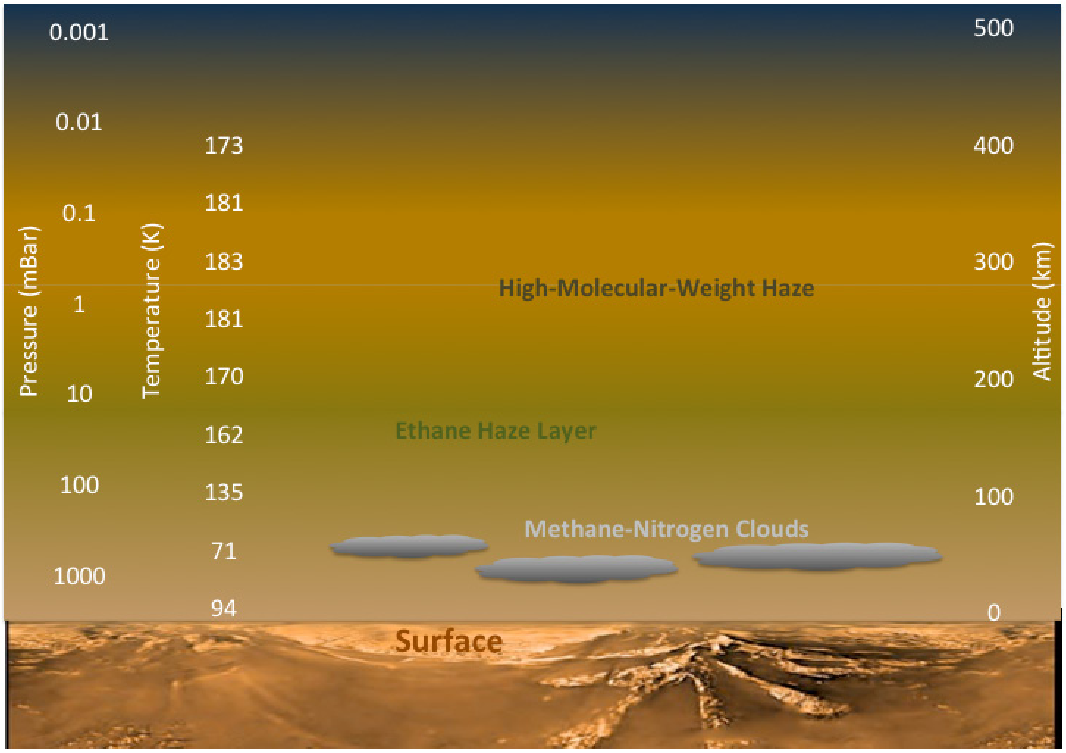


Figure 4.27.—Illustration of Titan atmosphere (Refs. 16 and 17).

TABLE 4.12.—PHYSICAL AND ORBITAL PROPERTIES OF TITAN (REFS. 16, 17, AND 18)

Property	Value
Maximum inclination of equator to orbit to Saturn (δ_{max})	0.35°
Orbital eccentricity (ε)	0.0288
Mean radius of orbit (r_m) around Saturn	1.22×10^6 km
Day period (synchronous to the orbital period around Saturn)	15.95 (Earth Days)
Surface pressure	146.7 kPa
Albedo	0.22
Gravitational constant (g_v)	1.35 m/s^2
Orbital period around Saturn	15.95 (Earth days)
Surface temperature	90 to 95K
Diameter	5152 km
Solar flux outside Titan's atmosphere	14.87 W/m^2
Speed of sound at the surface	196.5 m/s
Atmosphere gas constant (R_a)	296.8 J/kg-K
Atmosphere ratio of specific heats (γ_a)	1.4
Atmosphere specific heat (c_{pa})	1039 J/kg-K

The gravitational acceleration on Titan (1.35 m/s^2) is less than that of Earth's Moon. Liquid is present on the surface in the form of methane and ethane. These form the seas, as shown in Figure 4.28, in which the submarine will explore.

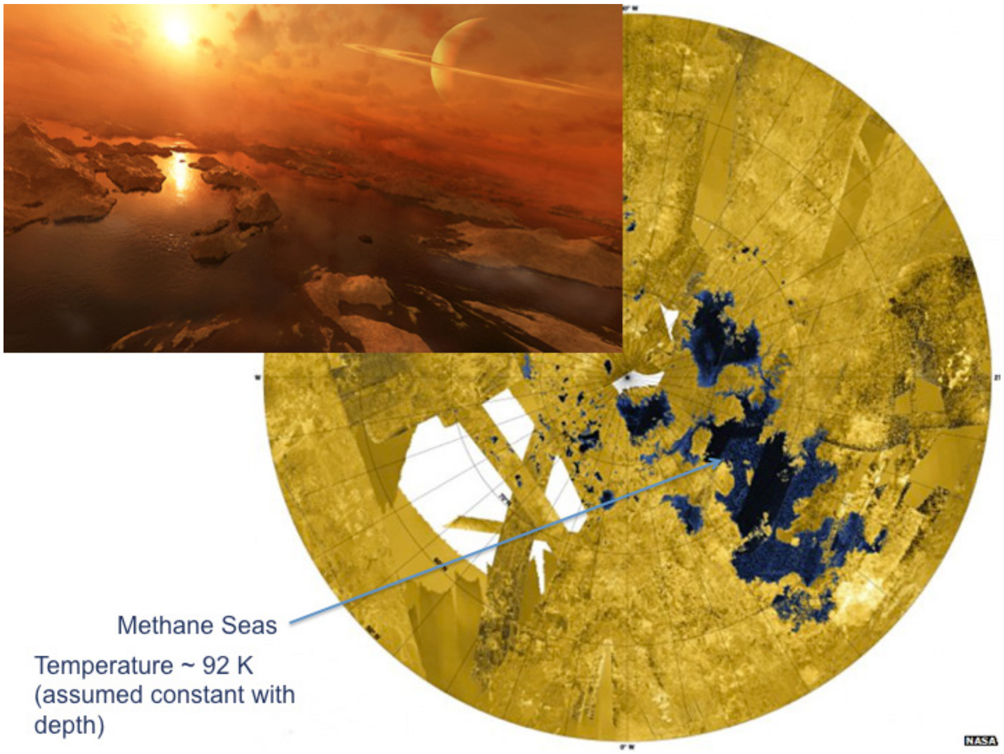


Figure 4.28.—Liquid methane seas on Titan.

4.7.2 Thermal Control in Transit to Titan

In deep space transit to Titan, the TCS has to protect and regulate the temperature of the submarine and entry vehicle. Excess heat from the isotope power system is used to maintain the desired internal operating temperature of the vehicle's components. However, the excess heat must also be rejected to deep space to avoid the interior of the submarine from becoming too warm. The heat generated by the isotope power system is rejected to space through the use of a radiator on the cruise deck and entry vehicle. Heat is transferred to the entry vehicle radiator through a series of cold plate interfaces contacting the outer structure of the submarine as well as a dedicated interface directly between the power system and the radiator. Since the system will need to reject approximately 3,800 W of heat, the direct coupling of the power system to the radiator is necessary. This is because if all of the heat were to be removed through the submarine structure the radiator operating temperature would need to be very low requiring an excessively large radiator. Heat loss through the submarine structure is the main means of cooling within the methane seas. Therefore, for this to be accomplished during transit and maintain the correct internal temperature, it would require the radiator to operate at a similar temperature to that of the liquid methane seas, approximately 92 K. To avoid the need for an excessively large radiator, heat is removed at a much higher temperature directly from the power source. Heat is transferred from the interior of the submarine to the entry vehicle radiator through an interior and exterior interface cold plate along with a coolant loop and heat pipes. This arrangement is illustrated in Figure 4.29. Once the submarine enters the Titan environment the heat flow to this interface radiator is shut off and the main submarine structure is now used to reject the excess heat.

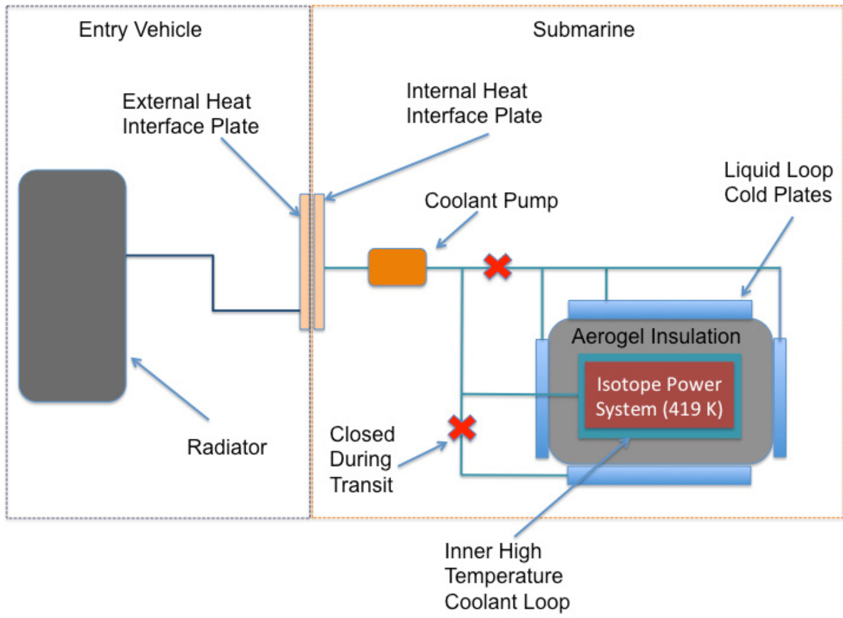


Figure 4.29.—Heat transfer from submarine to entry vehicle during transit.

TABLE 4.13.—THERMAL SYSTEM SPECIFICATIONS

Specifications	Value
Submarine Dimensions	Length 5-m by width 0.62-m: cylindrical shaped
Waste heat Provided by the isotope power system.	3800 W
Operating Temperature	Internal ~ 290 to 310 K (17 to 37 °C)
Insulation (aerogel foam)	3.0-cm thick enclosing the interior surface
Environment	Liquid methane and ethane at approximately 92 K (–181 °C)
Passthroughs: Structure Science	Two support rings connected to the outer shell Two windows 4 cm in diameter each Wiring for data and power transfer to the external equipment.
Isotope System	Heat rejection temperature of 419 K

4.7.3 Surface Operation Within the Liquid Methane Seas

For the internal components of the submarine to operate within the methane and ethane seas their temperature has to be maintained within their desired operating range. This temperature range, given in Table 4.13, is much higher than the temperature of the surrounding liquid. To achieve this, waste heat from the isotope power system is utilized to warm the submarine interior. The heat is then rejected through the structure and surface walls of the submarine to the exterior. The interior must be insulated to provide sufficient thermal resistance to achieve the desired internal temperature. This arrangement is shown in Figure 4.30 and the heat loss breakdown is shown in Figure 4.31.

The operation of the thermal system while in the Titan seas is illustrated in Figure 4.32. Excess heat is removed from the isotope system through a layer of insulation. The insulation allows the heat rejection temperature of the power system to be at 419 K while maintaining the interior temperature at 290 K. The heat on the outside of the insulation is picked up using a series of cold plates. A coolant loop is interfaced with the cold plates and is pumped to similar plates located along the submarine structure. This coolant loop system distributes the heat uniformly throughout the interior of the submarine. An example of a cold plate with integral coolant passages is shown in Figure 4.33.

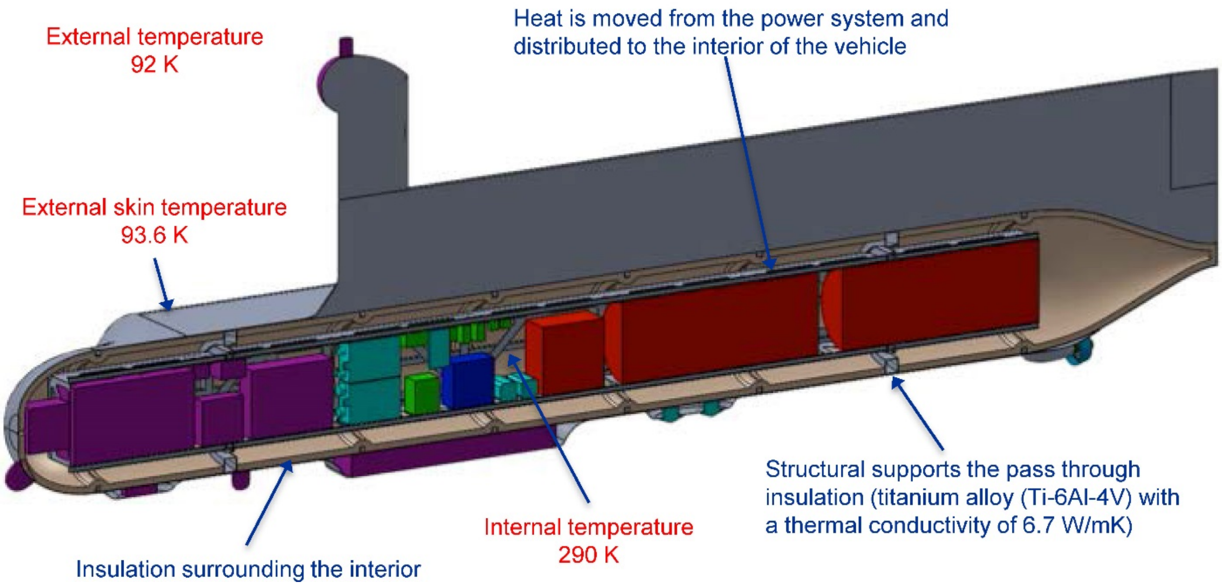


Figure 4.30.—Thermal management and temperatures within the submarine.

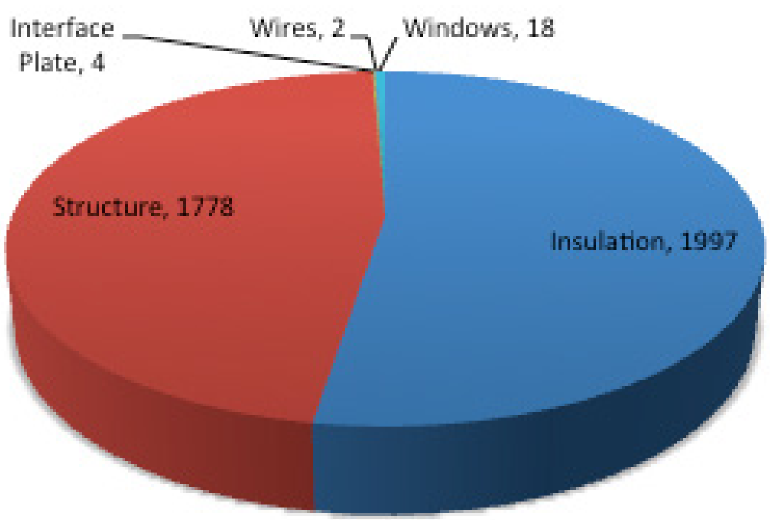


Figure 4.31.—Heat loss in Watts through the various paths within the submarine.

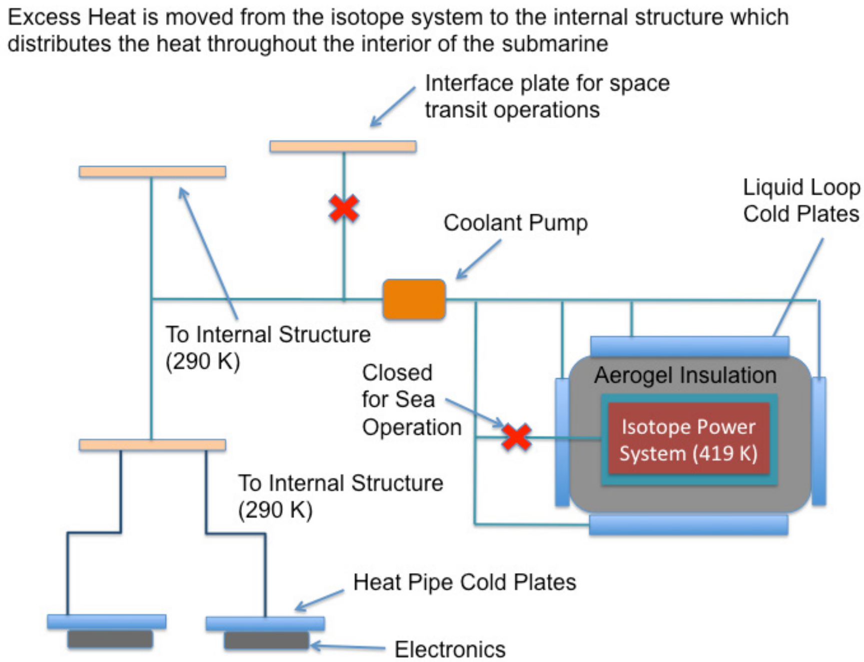


Figure 4.32.—Illustration of heat distribution system within the submarine.

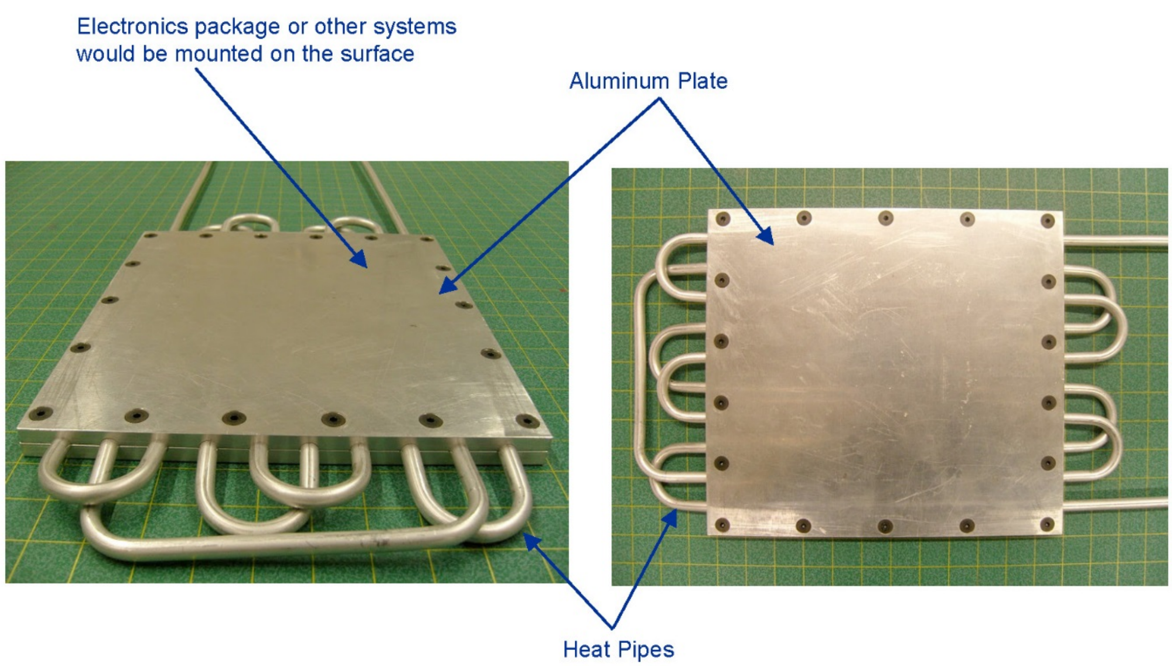


Figure 4.33.—Cold plate with integral coolant fluid flow tubes.

Aerogel foam is used to insulate the interior of the submarine. The insulation thickness is 3 cm. The insulation provides a very low conductivity barrier between the inside and the exterior walls of the submarine. The insulation has a thermal conductivity of 0.28 W/mK. This thermal conductivity is effectively the thermal conductivity of the nitrogen gas within the submarine. At the internal operating pressure of 150 psi, the insulation acts as a natural convection barrier and effectively allows only conduction through the gas as the main means of heat transfer through the insulation. There are two structural rings that extend through the insulation to provide a structure-mounting framework in the interior of the submarine. These structural pass-through members are constructed of a low conductivity titanium alloy (Ti-6Al-4V) with a thermal conductivity of 6.7 W/mK. Examples of aerogel insulation and its placement are shown in Figure 4.34.

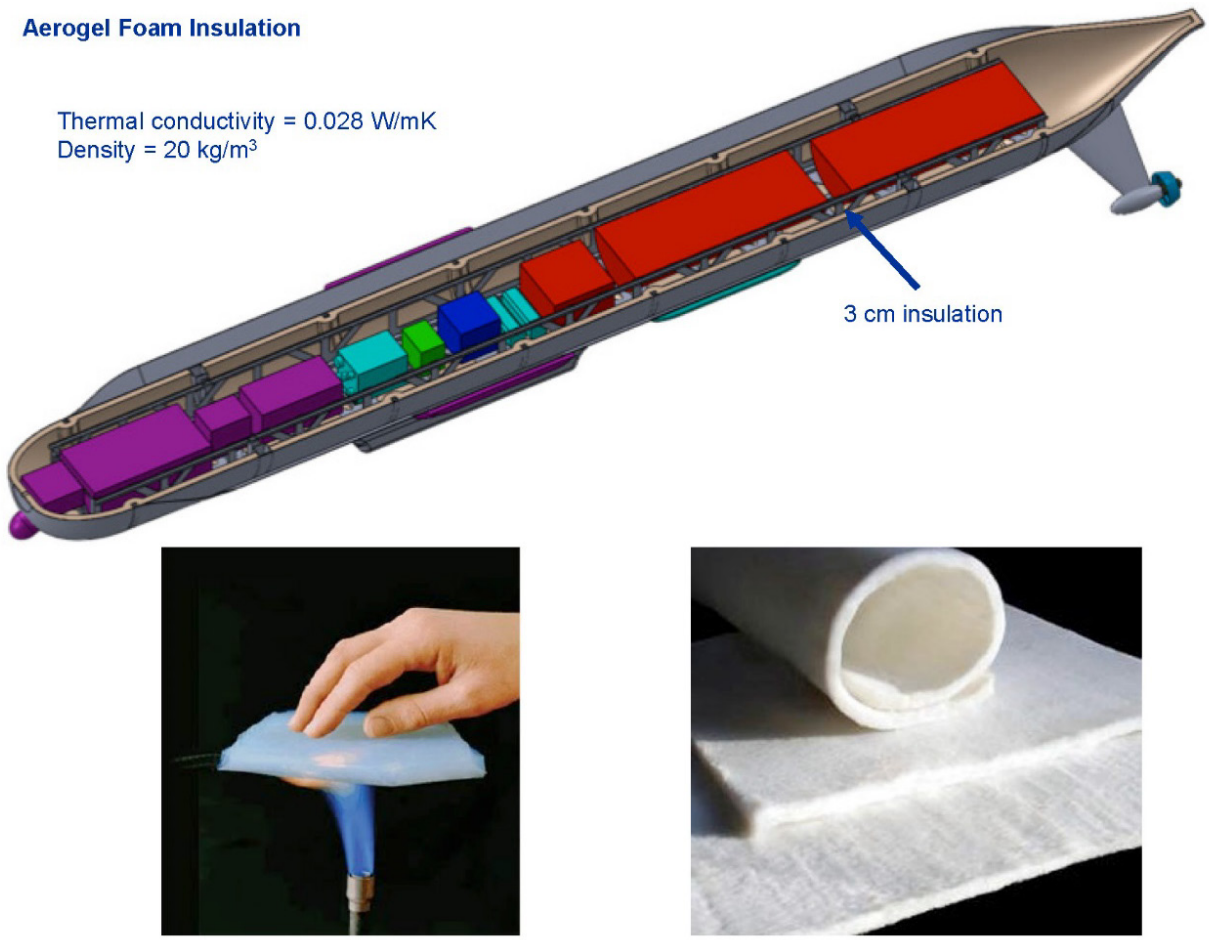


Figure 4.34.—Aerogel foam insulation placement within the submarine.

4.7.4 TCS MEL

The masses and mass growth allowances of the components of the Titan Sub's TCS are show in Table 4.14.

4.8 Structures and Mechanisms

4.8.1 Structures and Mechanisms Requirements

The structure of the Titan Submarine is comprised of a main hull and two ballast tanks, protected by an outer skin. The hull contains the majority of the submarine components, which are supported by two large rings and six smaller rings, all of which are connected and supported longitudinally by four beams. The other subsystems are supported by a truss inside the hull and four additional beams. The hull structure is required to provide support and protection for the science, AD&C, C&DH, communications instrumentation, thermal insulation, and propulsion subsystems of the submarine.

The submarine hull and the ballast tanks must be able to withstand an internal pressure of 1.03 MPa (150 psi) while undergoing pressurization with nitrogen, and must be able to withstand an expected external pressure of 1.03 MPa (150 psi) beneath the surface of Kraken Mare.

The goal of the design is to minimize weight of the structure while providing sufficient strength to withstand applied loads from the LV. The maximum anticipated vertical acceleration is 5 times that of gravity, and the maximum anticipated lateral acceleration is 2 times that of gravity. Titan's surface temperature is 94 K (–179 °C), and structural materials chosen should be able to withstand these low temperatures.

TABLE 4.14.—TCS MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Thermal Control (Non-Propellant)			95.3	18.0	17.2	112.5
Active Thermal Control			3.1	18.0	0.5	3.6
Thermal Control	15	0.20	3.0	18.0	0.5	3.5
Thermocouples	5	0.01	0.1	18.0	0.0	0.1
Passive Thermal Control			92.3	18.0	16.6	108.9
Insulation	1	6.21	6.2	18.0	1.1	7.3
Interface Plates	2	0.14	0.3	18.0	0.0	0.3
Coolant Loop and Fluid	1	3.53	3.5	18.0	0.6	4.2
Radiator	0	0.00	0.0	18.0	0.0	0.0
Thermal Paint	1	1.81	1.8	18.0	0.3	2.1
Coolant Pump	2	3.00	6.0	18.0	1.1	7.1
Power System Thermal Interface	2	0.14	0.3	18.0	0.0	0.3
Heat Pipes	10	1.69	16.9	18.0	3.0	19.9
Power System Insulation	1	0.87	0.9	18.0	0.2	1.0
Gas Pressurant Tank	2	6.99	14.0	18.0	2.5	16.5
Ne Gas	2	6.25	12.5	18.0	2.2	14.7
Gas Pressurant Pump	2	2.00	4.0	18.0	0.7	4.7
Buoyancy control valves	12	1.50	18.0	18.0	3.2	21.2
Ballast tank piston	4	2.00	8.0	18.0	1.4	9.4

The deployable camera boom mechanism is required to function for a single deployment. Also for the purposes of this study, installations for all other submarine subsystems were considered mechanisms in the MEL but are not described in this report.

4.8.2 Structures and Mechanisms Assumptions

The rings and outer skin of the submarine hull structure and ballast tanks are Ti-6Al-4V. Properties for Ti-6Al-4V are taken from the Metallic Materials Properties Development and Standardization (MMPDS-04) (IHS, 2008). The hull, skin, and ballast tanks of the submarine are assumed to be of primarily welded construction, along with threaded fasteners to join components. The outer skin surrounding the submarine hull and ballast tanks was assumed to be a high strength carbon fiber composite. The square tubular beams and truss structure inside the submarine hull were assumed to be of aluminum (Al) 2024-T8. This is a high strength Al with excellent resistance to fatigue, and is good for use in the submarine design because of its high strength to weight ratio. The drawbacks of Al 2024-T8 are that it may be expensive and difficult to weld.

The load inside the hull is carried through the two larger rings. It was assumed that the frame and rings of the structure would easily adapt to the aeroshell and LV via trunnion pins and keel fittings on the aerovehicle.

It was assumed that the maximum internal or external pressure the submarine hull, ballast tanks or outer skin would experience was 1.03 MPa (150 psi.)

4.8.3 Structures and Mechanisms Design and MEL

The Titan Submarine as designed is shown in Figure 4.35. The internal structure of the hull is shown in Figure 4.36.

The large rings have a 6.3- by 6.3-cm (2.5- by 2.5-in.) square cross section with a 0.25 cm (0.1 in.) wall thickness. The small rings have a 2.5- by 2.5-cm (1.0- by 1.0-in.) square cross section with a 0.25 cm (0.1 in.) wall thickness. Four 2.5- by 2.5-cm (1.0- by 1.0-in.) square beams, each with a 0.25 cm (0.1 in.) wall thickness are attached to the two large rings. Four additional 2.5- by 2.5-cm (1.0- by 1.0-in.) square beams each with a 0.25 cm (0.1 in.) wall thickness provide additional support to the Al alloy truss structure. These are attached to the larger rings, each with four additional shorter beams with a 3.8- by 3.8-cm (1.5- by 1.5-in.) square cross section with a 0.25 cm (0.1 in.) wall thickness.

The MEL for the Structures and Mechanisms of the Titan Submarine are show in Table 4.15.

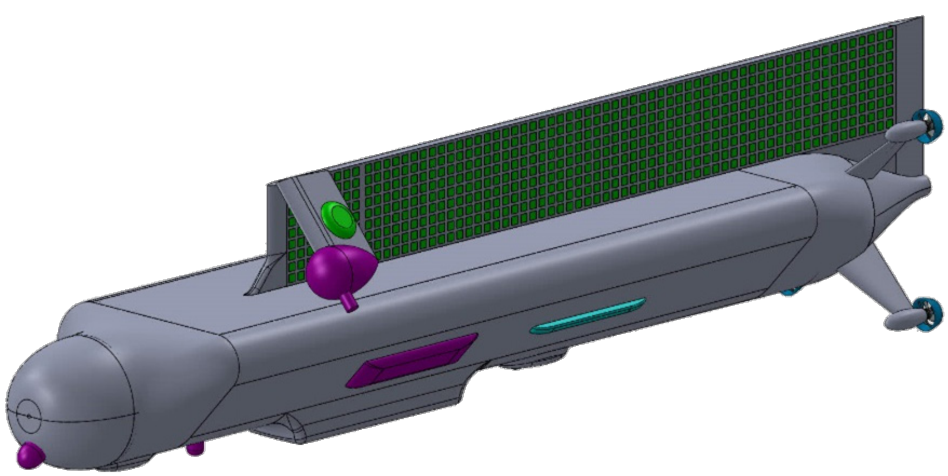


Figure 4.35.—Illustration of the Titan Submarine shown with undeployed camera boom.

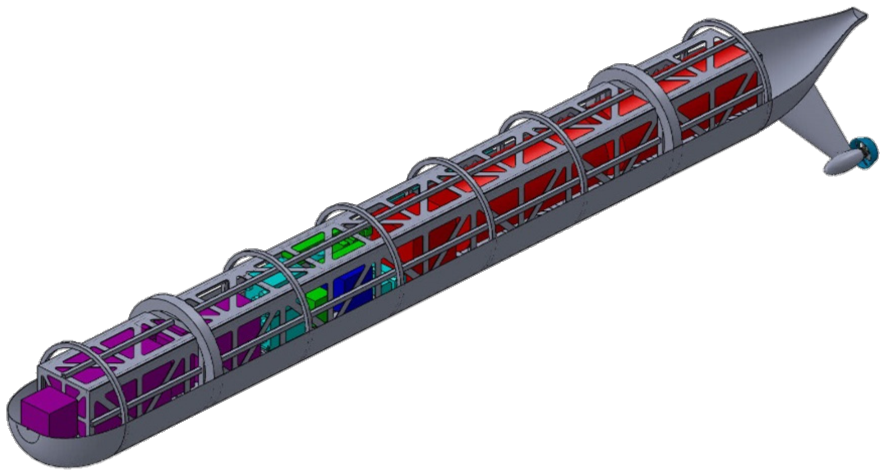


Figure 4.36.—Illustration of submarine hull internal structure.

TABLE 4.15.—TITAN SUBMARINE STRUCTURES AND MECHANISMS MEL

Description Case 1—Titan Sub CD-2014-114	Quantity	Unit mass, kg	Basic mass, kg	Growth, %	Growth, kg	Total mass, kg
Structures and Mechanisms	--	-------	445.7	18.0	80.2	525.9
Structures	--	-------	427.5	18.0	76.9	504.4
Primary Structures	--	-------	360.4	18.0	64.9	425.3
Pressure Hull	1	122.78	122.8	18.0	22.1	144.9
External Buoyancy Tanks	2	38.23	76.5	18.0	13.8	90.2
Tail Shell	0	0.00	0.0	18.0	0.0	0.0
Truss—hull	1	54.85	54.9	18.0	9.9	64.7
Bulkheads—Ballast Tanks	2	0.72	1.4	18.0	0.3	1.7
Stiffening beams	8	4.89	39.1	18.0	7.0	46.1
Boom for science instruments	1	0.99	1.0	18.0	0.2	1.2
Large rings	2	4.79	9.6	18.0	1.7	11.3
Small rings	6	1.81	10.9	18.0	2.0	12.8
Composite shell	1	44.30	44.3	18.0	8.0	52.3
Secondary Structures	--	-------	67.1	18.0	12.1	79.2
Antenna support—honeycomb	1	63.51	63.5	18.0	11.4	74.9
Antenna support—foam	0	34.60	0.0	0.0	0.0	0.0
cross stiffening beams	8	0.45	3.6	18.0	0.6	4.2
Mechanisms	--	-------	18.2	18.0	3.3	21.5
Science Payload	1	3.64	3.6	18.0	0.7	4.3
AD&C	1	1.32	1.3	18.0	0.2	1.6
C&DH	1	1.76	1.8	18.0	0.3	2.1
Comm and Tracking	1	1.05	1.1	18.0	0.2	1.2
Electrical Power System	1	5.84	5.8	18.0	1.1	6.9
Thermal Control (Non-propellant)	1	3.81	3.8	18.0	0.7	4.5
Propulsion	1	0.82	0.8	18.0	0.1	1.0

4.8.4 Structures and Mechanisms Trades

A Ti alloy was chosen for the majority of the structural components including the rings and skin of the hull of the submarine and the ballast tanks. Titanium was chosen because of its high strength to mass ratio. Aluminum alloy was chosen for the square beams and truss structure inside the submarine hull due to Al's lower density and thus reduced weight. Replacing the Al beams and truss structure with Ti could be considered if the expected structural loads, launch loads, or landing loads increase, or if higher safety margins are desired. Replacing the Al alloy parts with Ti alloy parts would result in increased strength but with increased mass. No other trades were discussed at this time.

4.8.5 Structures and Mechanisms Analytical Methods

First, cylindrical pressure vessel calculations were performed in order to determine a sufficient wall thickness for the Ti-6Al-4V submarine hull and ballast tanks to withstand the 1.03 MPa (150 psi) internal air pressure while undergoing pressurization prior to launch. Though the minimum wall thickness was calculated to be 0.076 cm (0.03 in.), a wall thickness of 0.25 cm (0.1 in.) was chosen to ensure stability. Buckling equations were then applied to the Ti alloy outer shell to determine whether the shell itself was susceptible to buckling under a 5 g load. Per Euler's buckling formula, the critical buckling stress would be so high that the submarine hull would be likely to exceed the yield stress before the outer shell would buckle under an axial load.

A preliminary structural analysis was performed on a simplified version of the submarine hull structure using ANSYS workbench version 15.0. Because launch loads are expected to be the highest loads on the submarine, the ±5 g axial acceleration loads and 2 g lateral acceleration loads were examined. The ANSYS model consisted of the cylindrical portion of the hull with the outer Ti alloy shell, two large rings and five smaller rings. The cylindrical portion of the submarine hull in the analysis was assumed to be 67.5 cm (26.6 in.) in diameter and 4.6 m (182 in.) in length. The Al alloy square beams running the length of the cylindrical portion of the hull were also 4.6 m (182 in.) in length. The Ti alloy rings were equally spaced along the length of the hull, and point masses were used to represent non-structural subsystems.

Material properties were used at their room temperature condition since launch loads, the highest expected loads, would occur near room temperature. Properties were taken from MMPDS-04. For Ti-6Al-4V, an ultimate strength of 924 MPa (134,000 psi) and yield strength of 869 MPa (126,000 psi) were used. For Al 2024-T8, an ultimate strength of 455 MPa (66,000 psi) and yield strength of 400 MPa (58,000 psi) were used. Figure 4.37 to Figure 4.40 show the ± 5g axial model and the 2g lateral model in ANSYS.

Of all three loading conditions, the maximum deflections and equivalent stresses occurred in the 2g lateral acceleration case. The maximum stress in this case was 219.3 MPa (31,799 psi), which occurred on the 2024 Al alloy beam. Using an ultimate factor of safety of 1.4 and yield factor of safety of 1.25 per NASA-STD-5001, corresponding to protoflight hardware, the margin of safety against ultimate failure is +0.48 and margin of safety against yield is +0.46.

The preliminary version of the structure as analyzed is a very simplified version of the final design of the submarine hull structure, which includes four more square Al beams, cross-beams for stabilization, and a truss structure to hold the other subsystems. See Figure 4.41 and Figure 4.42 for preliminary simplified submarine hull model compared with the final design with additional beams and truss structure. The final design of the submarine hull structure is strong enough with enough margin to withstand expected maximum launch loads. A detailed analysis of the final design was beyond the scope of the 3 wk study, but will be included in the next phase of the project.

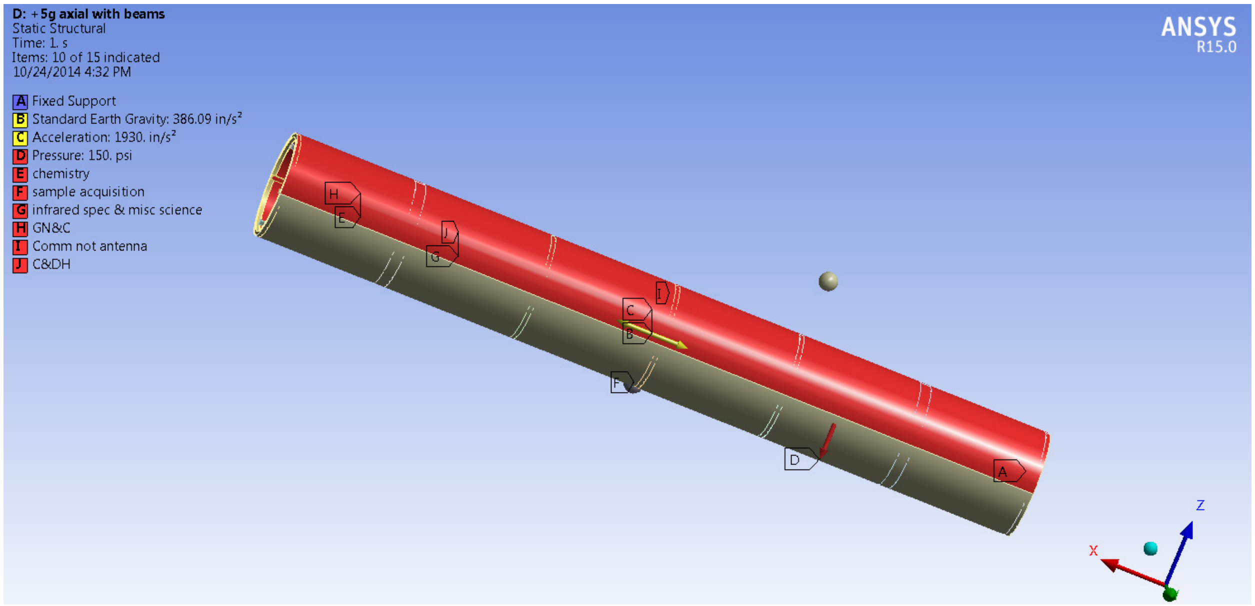


Figure 4.37.—Static structural model of simplified submarine hull structure with +5g axial load.

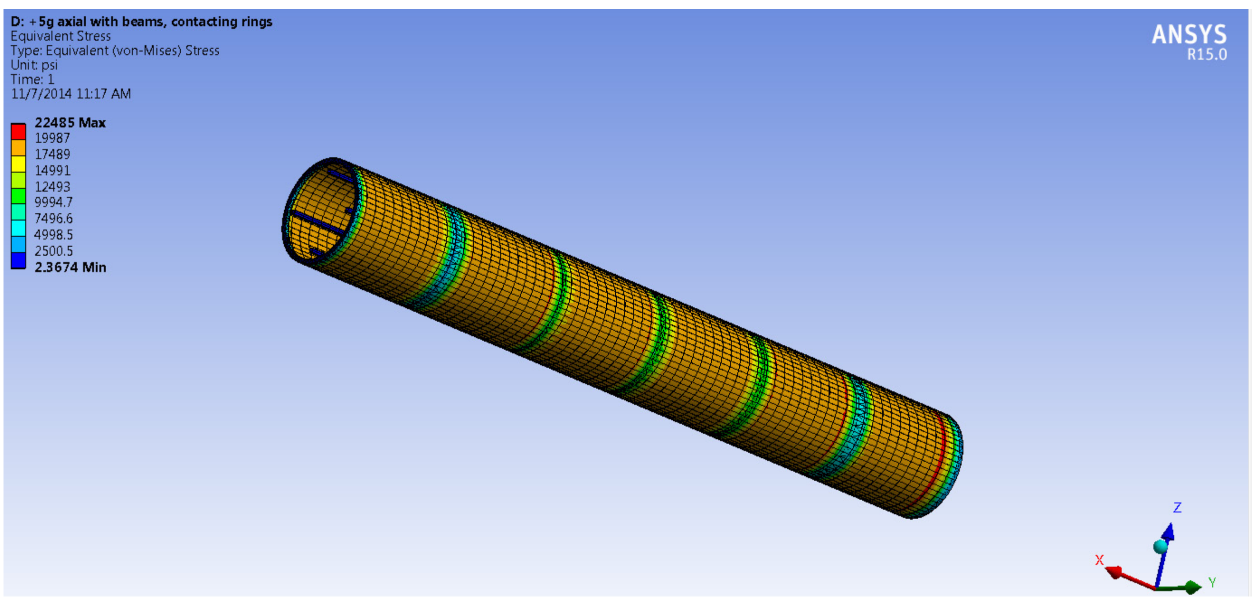


Figure 4.38.—Maximum equivalent stresses (in psi) for simplified submarine hull structure with +5g axial load.

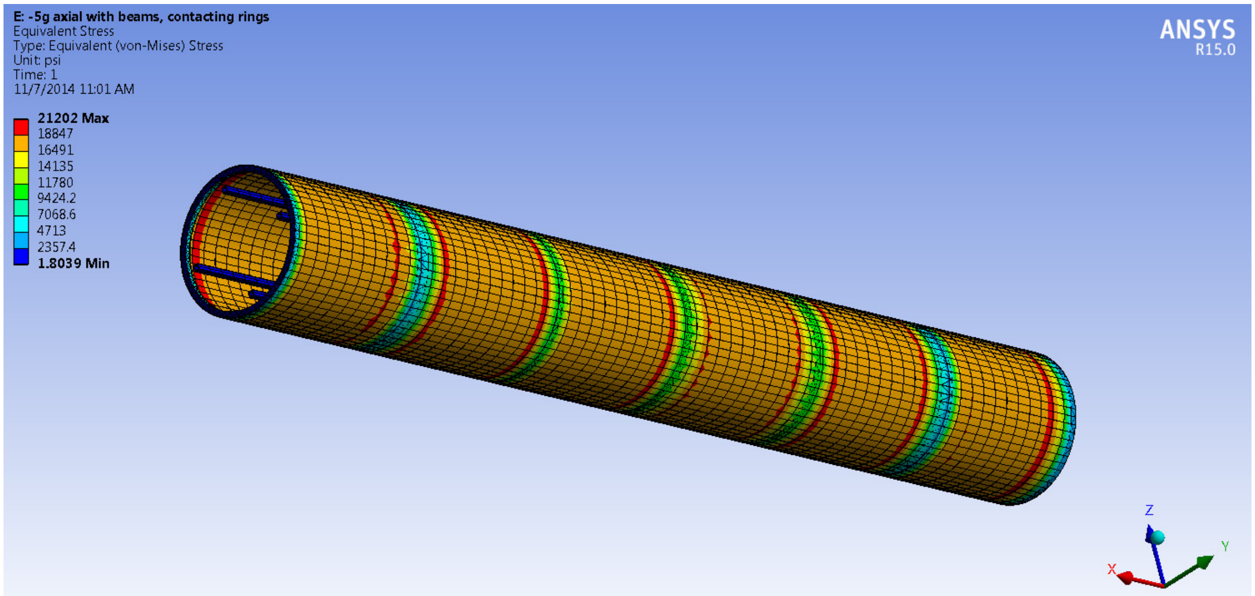


Figure 4.39.—Maximum equivalent stresses (in psi) for simplified submarine hull structure with -5g axial (x) load.

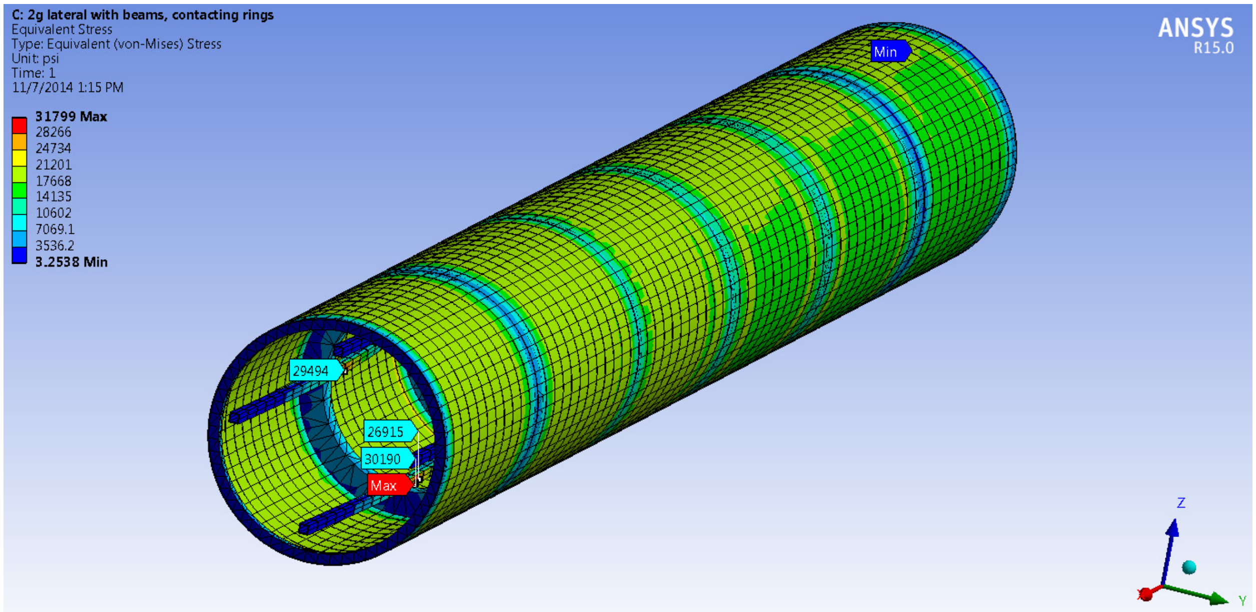


Figure 4.40.—Maximum equivalent stresses (in psi) for simplified submarine hull structure with 2g lateral (y) load.

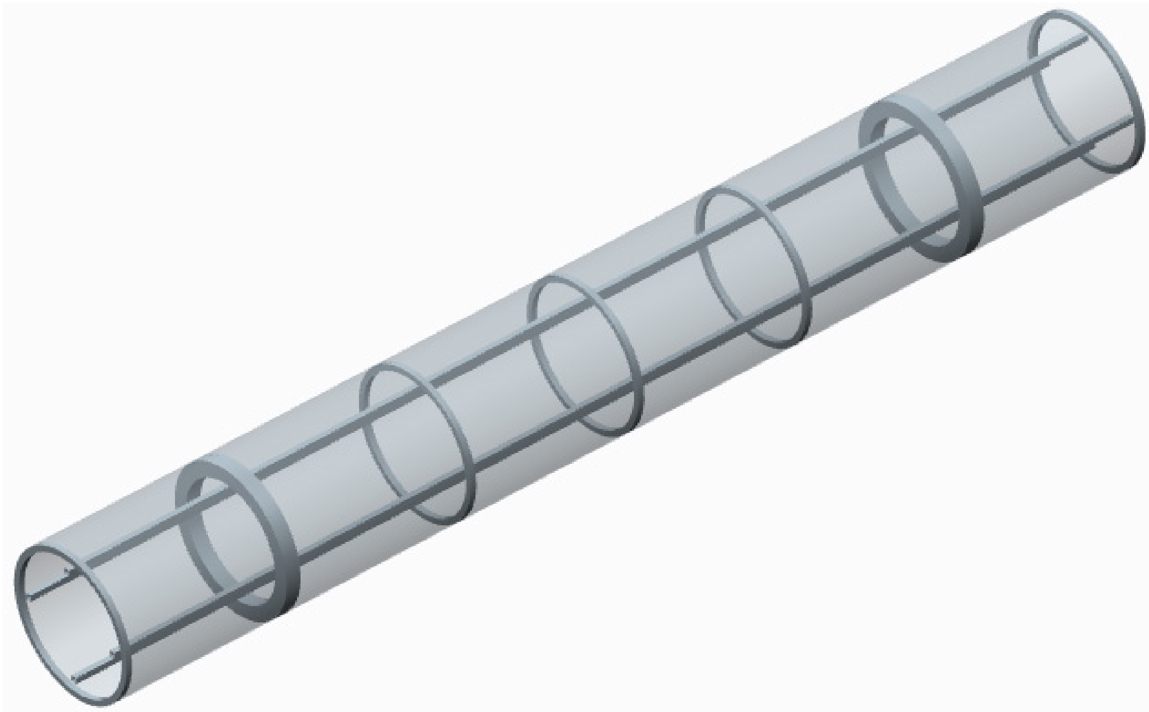


Figure 4.41.—Preliminary simplified Titan Submarine hull model.

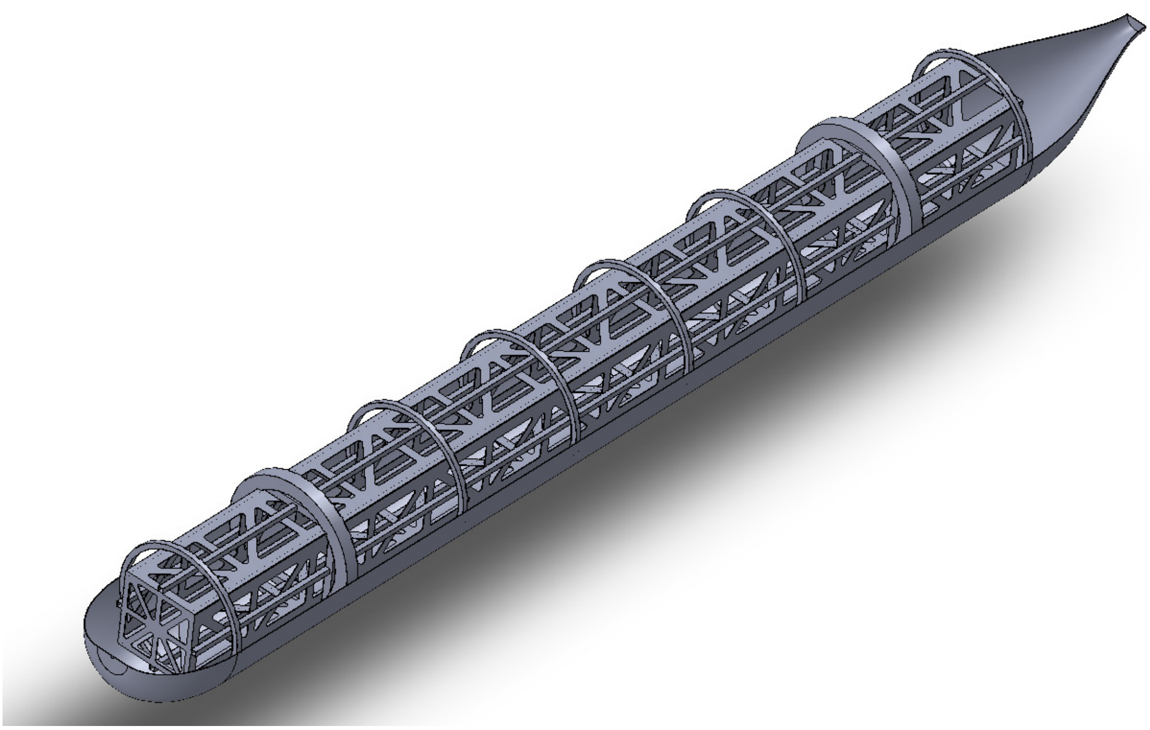


Figure 4.42.—Final Titan Submarine hull design.

4.8.6 Structures and Mechanisms Risk Inputs

Structural risks may include excessive g loads, impact from a foreign object, or a harsh landing on Titan which may cause excessive deformation, vibration, or even fracture of sections of the Submarine support structure. Consequences include reduced performance from mounted hardware to loss of mission.

In an effort to mitigate the structural risk, the structure is designed to NASA standards to withstand expected g loads and to have sufficient stiffness and damping to minimize issues with vibrations. Trajectories are to be planned to minimize the probability of impact with foreign objects. The likelihood for structural risks is low at 2. The cost would be given a rating of 3. The mission schedule and performance would each receive a rating of 4. As an unmanned mission, there would be no risk to humans making the risk safety a low rating of 1.

4.8.7 Structures and Mechanisms Recommendations

The Titan Submarine structure is designed to NASA standards to withstand expected g loads and to have sufficient stiffness and damping to minimize issues with vibrations.

5.0 Titan Submarine Cost Estimate

5.1 Ground Rules and Assumptions

The following ground rules and assumptions apply to the mission cost estimates:

- The scope of the estimate is the design and development and flight hardware for the submarine only. It does not include launch and cruise deck/lifting body, reserves, or any technology development up to TRL level 6.
- The estimate assumes the SRG has competed development and qualification testing. The cost of GPHUs/plutonium is not included.
- Protoflight development of the submarine.
- Quantitative risk analysis performed using a Monte Carlo simulation driven by input parameter uncertainty and error statistics of the cost estimating relationships (CERs.)
- Costs presented are mode values (approximately 35th percentile), in constant FY15 dollars.
- Coefficient of Variance (Standard Deviation/Mean) of the estimate is approximately 38 percent.

5.2 Estimating Methodology

The submarine estimate was developed using a Microsoft Excel-based parametric cost model created for this study. The model uses an approach similar to NAFCOM, i.e., the subsystem hardware and software elements of a product-oriented WBS were estimated primarily using parametric CERs and the sum of the subsystem costs were used to estimate system integration costs. The primary input to the submarine cost model was the MEL developed by the COMPASS team for this study; most of the CERs use mass as at least one of the independent parameters. The submarine WBS in the MEL is mapped to the cost estimate WBS, which in several cases rolls up multiple elements to create elements consistent with the most applicable CERs (Table 5.1). Most CERs were developed in-house using “ZMPE” (zero-bias, minimum percent error) regression analysis, and are based on as many relevant data points as available so the standard errors used to develop the risk model would have a strong statistical basis (Figure 5.1).

5.3 Submarine Cost Estimates

Note: the following abbreviations are used for the systems integration elements: Integration, Assembly and Check-out (IACO), Systems Test Operations (STO), Ground Support Equipment Hardware

(GSE), Systems Engineering and Integration (SE&I), Program Management (PM) and Launch and Orbital Operations Support (LOOS). For more detailed explanation of integration costs, see Section 5.4.

TABLE 5.1.—TITAN SUBMARINE COSTS AT THE SUBSYSTEM LEVEL (CONSTANT FY15 $M)

WBS/Description		DDT&E Total (FY15$M)	Flight HW Total (FY15$M)	DD&FH Total (FY15$M)
06.1.1	Science Payload	183	34	217
06.1.2	AD&C	36	9	45
06.1.3	C&DH	57	15	71
06.1.4	Communications and Tracking	18	5	23
06.1.5	Electrical Power Subsystem	15	43	57
06.1.6	Thermal Control (Non-Propellant)	33	8	40
06.1.7	Propulsion	3	2	5
06.1.11	Structures and Mechanisms	26	14	39
	Subsystem Subtotal	371	128	498
Systems Integration				37
IACO and STO		31	6	
GSE Hardware		45	0	45
SE&I		59	6	65
PM		32	14	46
LOOS		37	0	37
	Spacecraft Total	574	154	728

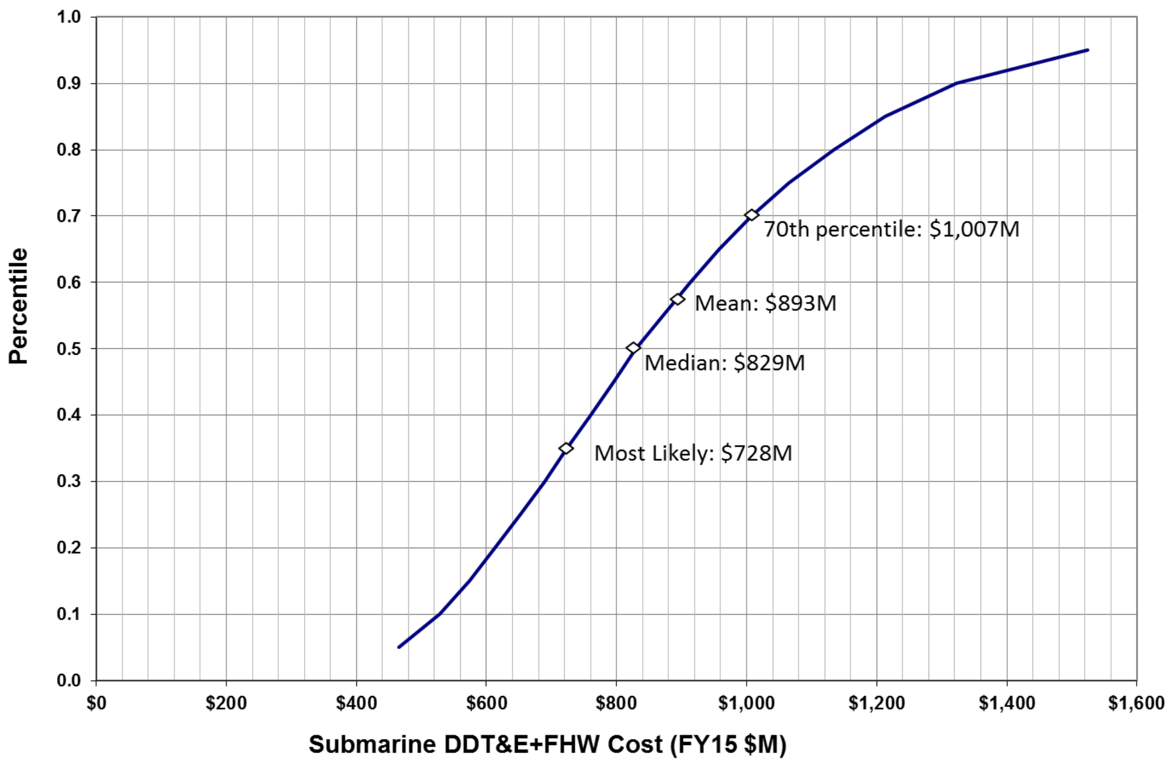


Figure 5.1.—Titan Submarine cost/risk curve (Constant FY15 $M).

5.4 Definitions

5.4.1 Integration, Assembly and Checkout (IACO)

The IACO element contains all labor and material required to physically integrate (assemble) the various subsystems into a total system. Final assembly, including attachment, and the design and manufacture of installation hardware, final factory acceptance operations, packaging/crating, and shipment are included. IACO charged to DDT&E represents those costs incurred for the integration, assembly, and checkout of major test articles. IACO charged to the flight unit includes those same functions applied to the actual flight unit.

This item excludes the engineering effort required to establish the integration, assembly, and checkout procedures necessary for this effort. These engineering efforts are covered under systems engineering and integration.

5.4.2 System Test Operations (STO)

The STO element includes development testing and the test effort and test materials required for qualification and physical integration of all test and qualification units. Also included is the design and fabrication of test fixtures.

Specifically included are tests on all System Test Hardware (STH) to determine operational characteristics and compatibility with the overall system and its intended operational parameters. Such tests include operational tests, design verification tests, and reliability tests. Also included are the tests on systems and integrated systems to verify acceptability for required mission performance. These tests are conducted on hardware that has been produced, inspected, and assembled by established methods meeting all final design requirements. Further, system compatibility tests are included, as well as, functions associated with test planning and scheduling, data reduction, and report preparation.

5.4.3 Ground Support Equipment (GSE)

Functional elements associated with GSE include the labor and materials required to design, develop, manufacture, procure, assemble, test, checkout, and deliver the equipment necessary for system level final assembly and checkout. Specifically, the equipment utilized for integrated and/or electrical checkout, handling and protection, transportation, and calibration, and items such as component conversion kits, work stands, equipment racks, trailers, staging cryogenic equipment, and many other miscellaneous types of equipment are included.

Specifically excluded is the equipment designed to support only the mission operational phase.

5.4.4 Systems Engineering and Integration (SE&I)

The functions included in the SE&I element encompass: (1) the system engineering effort to transform an operational need into a description of system requirements and/or a preferred system configuration; (2) the logistics engineering effort to define, optimize, and integrate logistics support considerations to ensure the development and production of a supportable and cost effective system; and (3) the planning, monitoring, measuring, evaluating, and directing of the overall technical program. Specific functions include those for control and direction of engineering activities, cost/performance trade-offs, engineering change support and planning studies, technology utilization, and the engineering required for safety, reliability, and quality control and assurance. Also included is the effort for system optimization, configuration requirements analyses, and the submittal and maintenance of Interface Control Documents (ICDs).

Excluded from the SE&I element are those functions which are identifiable to subsystem SE&I.

5.4.5 Program Management (PM)

Elements included in the PM function consist of the effort and material required for the fundamental management direction and decision making to ensure that a product is developed, produced, and delivered.

Specifically included are direct charges for program administration, planning and control, scheduling and budgeting, contracts administration, and the management functions associated with engineering, manufacturing, support, quality assurance, configuration and project control, and documentation.

The PM element sums all of the effort required for planning, organizing, directing, coordinating, and controlling the project to help ensure that overall objectives are accomplished. This element also includes the effort required to coordinate, gather, and disseminate information.

Those functions commonly charged to subsystem level activities are excluded from the PM element.

5.4.6 Launch and Orbital Operations Support (LOOS)

This category includes the effort associated with pre-launch planning, launch and ascent, and initial on-orbit operations. The pre-launch activities include bus and payload preparation, as well as interface activities with the LV.

The launch and ascent period includes final assembly, checkout, and fueling, lift-off, telemetry, pre-launch, telemetry, tracking and command, recovery operations, and post-processing of lift-off data. Support during the mission includes drive planning and science operation, attitude and orbit control, support of on-orbit testing, routine monitoring and fault detection of space vehicle subsystem functions, and support of anomaly investigation and correction. This period ends when the newly deployed satellite is turned over to the operational user, typically after a period of 30 days.

6.0 Phase II Study Plans

The following is summary of conceptual design activities that would be conducted under a Phase II NIAC study

- Examine Science Payload in more detail (e.g., immersion-tolerant meteorology package; seabed sampling options, etc.)
- Evaluate subsurface communication DTE, and via Relay orbiter, noting RF transparency of some Titan liquids
- Evaluate impact on CONOPS and downlink data benefit of a relay orbiter, identify most useful complementary science from orbiter (e.g., could a space borne radar detect the sub or its wake?)
- Create a conceptual design of the aerovehicle/Titan entry system and create a MEL for that system
    - Develop the details of SRG installation accommodations, procedures and GSE required
    - Assess thermal protection system capability to withstand Titan entry heating
    - Assess sub mounting in aerovehicle
    - Assess systems for separation of aerovehicle from sub after Titan splashdown
    - Assess detailed LV interfaces including LV adapter
- Perform trajectory design to determine LV performance requirement, transit time to Titan, and any necessary planetary gravity assist maneuvers required to assure sub arrival at Titan summer
- Assess other Titan entry systems based on entry speed and heating
    - Inflatable heat shield/decelerator
- Assess alternative methodologies for Titan descent and splashdown
    - Circular chutes and guided parasail landing system

- Assess alternate sub deployment schemes from entry system
    - Sub separation after splashdown
    - Sub separation before splashdown (separate splashdowns of sub and entry system)
- Assess required targeting to assure landing on Kraken Mare
- Analyze communications systems requirements for the trans-Saturn cruise phase, and the Titan EDL phases of the Titan Submarine mission
- Perform basic physics testing of liquid ethane saturated with nitrogen to evaluate the 'effervescence' issue.

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Appendix.—Acronyms and Abbreviations

ΔV	delta velocity
ACS	Auxiliary Cooling System
AD&C	Attitude, Determination & Control
AIAA	American Institute for Aeronautics and Astronautics
Al	aluminum
ANSI	American National Standards Institute
ANSYS	Analysis System
APL	Applied Physics Laboratory
ASC	Advanced Stirling Convertor
AUV	automated underwater vehicle
BOL	beginning of life
BOM	beginning of mission
BSA	Benthic Sample Acquisition
C&DH	Command and Data Handling
C/CAM	Collision and Contamination Avoidance Maneuver
CAD	computer aided design
CAP	Chemistry Analysis Package
CB	center of buoyancy
CBE	current best estimate
CCAFS	Cape Canaveral Air Force Station
CCD	charged-couple device
CER	cost estimating relationships
CG	center of gravity
Comm	communications
COMPASS	COllaborative Modeling and Parametric Assessment of Space Systems
CONOPS	Concept of Operations
DC	direct current
DDT&E	design, development, test, and evaluation
DOE	Department of Energy
DOF	degree(s) of freedom
DOR	Differential One-way Ranging
DS	Depth Sounder
DSN	Deep Space Network
DTE	direct to Earth
DVL	Doppler Velocity Log
EDL	entry, descent and landing
EDS	entry, descent and splashdown
ELV	expendable launch vehicle
EOL	end of life
EOM	end of mission

EP	electric propulsion
FOM	figure(s) of merit
FPS	Fission Power System
FY	fiscal year
GCM	Global Circulation Models
GCMS	Gas Chromatograph Mass Spectrometer
GLIDE	GLobal Integrated Design Environment
GN&C	Guidance, Navigation, and Control
GPHS	general purpose heat source
GRC	NASA Glenn Research Center
GSE	ground support equipment
HPF	Hazardous Processing Facility
HQ	NASA Headquarters
HW	hardware
IACO	Integration, Assembly and Check-Out
IAU	International Astronomical Union
IMU	inertial measurement unit
INS	Inertial Navigation System
INSRP	Interagency Nuclear Safety Review Panel
IR	infrared
IRS	Infrared Spectrometer
ISS	International Space Station
JHU	Johns Hopkins University
JPL	NASA Jet Propulsion Laboratory
KSC	NASA Kennedy Space Center
LBL	Long Baseline
LEO	low Earth orbit
LNG	liquefied natural gas
LOM	loss of mission
LOOS	Launch and Orbital Operations Support
LSP	Launch Service Program
LSSM	Launch Site Support Manager
LSSP	Launch Site Support Plan
LSTO	Launch Service Task Order
LV	launch vehicle
MAHLI	Mars Hand Lens Imager
MECO	main engine cutoff
MEL	Master Equipment List
MET	Meteorology Package
MGA	mass growth allowance
miniTES	Miniature Thermal Emission Spectrometer

MLI	multilayer insulation
MMH	monomethyl hydrazine
MMOD	micrometeoroid and orbital debris
MMPDS	Metallic Materials Properties Development and Standardization
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOSB	Multi-Operation Support Building
MSL	Mars Science Laboratory
MS-MS	tandem mass spectrometry
N/A	not applicable
N_2O_4	dinitrogen tetraoxide
NASA	National Aeronautics and Space Administration
NAV	Navigation Systems
Ne	neon
NIAC	NASA's Innovative Advanced Concepts
NIST	National Institute of Standards and Technology
NLS	NASA Launch Services
NPR	NASA Procedural Requirements
OTS	off-the-shelf
P3	Physical Properties Package
PEL	Power Equipment List
PHSF	NASA Payload Hazardous Servicing Facility
PM	Program Management
PMAD	Power Management and Distribution
PPF	Payload Processing Facility
PPU	power processing unit
PRM	periapse raise maneuver
PSAR	Preliminary Safety Analysis Report
PSU	Pennsylvania State University
PSW	Payload Systems Weight
RCS	Reaction Control System
REMS	Rover Environmental Measurement System
REP	radioisotope electric propulsion
RF	radio frequency
ROV	Remotely Operated Vehicles
RPS	Radioisotope Power System
RTG	radioisotope thermoelectric generators
RTG-F	Radioisotope Thermoelectric Generator Facility
S/C	spacecraft
SA	solar array
SADA	solar array drive assembly
SAM	Sample Analysis at Mars

SAR	Safety Analysis Report
SDST	Small Deep Space Transponder
SE&I	Systems Engineering and Integration
SEC	Single-Engine Centaur
SER	Safety Evaluation Report
SI	Surfaced Imager
SIP	Standard Interface Plane
SLOC	source lines of code
SLS	Space Launch System
SMA	semimajor axis
SMC	System Memory Card
SMD	NASA's Science Mission Directorate
SOFC	solid oxide fuel cell
SOFI	spray-on foam insulation
SRB	solid rocket boosters
SRD	System Requirements Document
SRG	Stirling Radioisotope Generators
SS	Sidescan Sonar
SSP	Surface Science Package
STH	System Test Hardware
STO	Systems Test Operations
TBD	to be determined
TBR	to be resolved
TCS	Thermal Control System
TDRSS	Tracking and Data Relay Satellite System
TE	thermoelectric
Ti	titanium
TiME	Titan Mare Explorer
TRL	technology readiness level
TSSM	Titan Saturn System Mission
TTI	trans-Titan insertion
TWTA	traveling wave tube amplifier
UI	Undersea Imager
ULA	United Launch Alliance
UMo	uranium-molybdenum
USBL	ultra-short baseline
USO	ultra-stable oscillator
UUV	Unmanned Underwater Vehicle
UVS	ultraviolet sensor
VIF	Vertical Integration Facility
VPF	Vertical Processing Facility

VVJ	Venus-Venus-Jupiter
WBS	work breakdown structure
WGA	weight growth allowance
WGS	weight growth schedule
Xe	xenon
ZMPE	zero-bias, minimum percent error